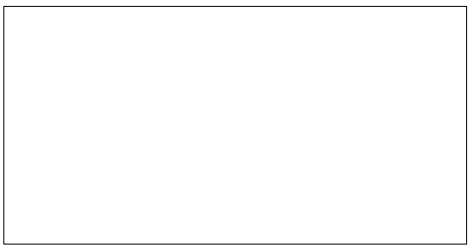

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***Title page**

rTMS evidence for a dissociation in short-term memory for spoken words and nonwords

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Abstract

Differing patterns of verbal short-term memory (STM) impairment have provided unique insights into the relationship between STM and broader language function. Lexicality effects (i.e., better recall for words than nonwords) are larger in patients with phonological deficits following left temporoparietal lesions, and smaller in patients with semantic impairment and anterior temporal damage, supporting linguistic accounts of STM. However, interpretation of these patient dissociations are complicated by (i) non-focal damage and (ii) confounding factors and secondary impairments. This study addressed these issues by examining the impact of inhibitory transcranial magnetic stimulation (TMS) on auditory-verbal STM performance in healthy individuals. We compared the effects of TMS to left anterior supramarginal gyrus (SMG) and left anterior middle temporal gyrus (ATL) on STM for lists of nonwords and random words. SMG stimulation disrupted nonword recall, in a pattern analogous to that observed in patients, compatible with a role for this site in processing speech sounds without support from long-term lexical-semantic representations. Stimulation of ATL, a semantic site, disrupted the recall of words but not nonwords. A visual pattern memory task indicated that these effects of TMS were restricted to the verbal domain. These data provide convergent evidence for the conclusions of neuropsychological studies that support linguistic accounts of verbal STM.

Introduction

Neuropsychological studies have played an important role in the development of neurological models of short-term memory (STM). These studies show double dissociations between phonological and semantic STM impairment, suggesting that several independent abilities contribute to verbal STM. Patients with phonological STM deficits show relatively selective difficulties in Immediate Serial Recall (ISR) for nonwords but not words, while those with semantic STM deficits show a reduced influence of imageability but relatively normal nonword ISR. Double dissociations have also been reported in probe recognition: when matching a probe word to items in a list presented a few seconds before, based on either the semantic or phonological characteristics of the words, patients can show relatively-selective deficits in category or rhyme matching, even when they can make the same judgements to single items with a high degree of accuracy (Freedman & Martin, 2001; R. C. Martin, Lesch, & Bartha, 1999; R. C. Martin, Shelton, & Yaffee, 1994). This pattern licences a revision of the original phonological loop model proposed by Baddeley and Hitch (1974), who anticipated a unitary verbal STM capacity.

The dissociation between semantic and phonological tasks in some cases appears to be relatively selective to STM. Nevertheless, in a broader sample of patients, studies have shown a strong association between STM deficits for phonological or semantic content and broader language deficits within these domains (Hoffman, Jefferies, Ehsan, Jones, & Lambon Ralph, 2012, 2009; Jefferies, Hoffman, Jones, & Lambon Ralph, 2008; Jefferies, Jones, Bateman, & Lambon Ralph, 2005; N. Martin & Saffran, 1997; Verhaegen, Piertot, & Poncelet, 2013): patients who show the hallmarks of semantic STM deficits tend to have difficulties in semantic tasks in which STM loads are minimal, and likewise patients with phonological STM deficits tend to have associated problems in phonological processing more generally. This observation led to a 'language systems' view of verbal STM, in which STM capacity was seen as an emergent property of linguistic processing within phonological and semantic systems. These accounts anticipate that interactions between semantic and phonological representations that support language tasks more broadly also underpin the capacity to sustain linguistic information over time. As a consequence, patients with phonological impairment, typically consequent of stroke aphasia, can show greater reliance on meaning to support phonological sequences – for

example, such cases may show an increased effect of imageability (Jefferies, Crisp, & Lambon Ralph, 2006; Reilly et al., 2012), while patients with semantic impairment, such as those with semantic dementia, show reduced effects of lexicality as their capacity to repeat nonwords is largely spared but ISR for sequences of words that are not fully understood is impaired (Hoffman, Jefferies, Ehsan, Jones, et al., 2009; Jefferies, Bott, Ehsan, & Lambon Ralph, 2011; Jefferies, Crisp, et al., 2006; Jefferies et al., 2008; Jefferies, Jones, Bateman, & Lambon Ralph, 2004; Jefferies et al., 2005; Knott, Patterson, & Hodges, 2000; Majerus, Norris, & Patterson, 2007).

To summarise, while a small number of cases show a dissociation between general language ability and STM performance (c.f., Vallar & Baddeley, 1984; Vallar, Di Betta, & Silveri, 1997; Warrington & Shallice, 1969), the majority of patients show an association (i.e., a link between STM performance and their broader language function/performance). It has been suggested that phonological deficits specific to STM tasks might occur in cases with very mild impairment, while semantic deficits specific to STM tasks might occur in people with very mild semantic access problems linked to difficulties in controlling semantic retrieval (Hoffman, Jefferies, Ehsan, Hopper, & Lambon Ralph, 2009; Hoffman, Jefferies, & Lambon Ralph, 2011). Current accounts of verbal STM are in agreement that an important role is played by long-term linguistic representations. However, there is still controversy about the nature of the relationship between verbal STM capacity and broader language processing, with some theories anticipating a more direct link in which verbal STM is indistinguishable from ongoing language processing (e.g., Acheson & MacDonald, 2009; Jefferies, Frankish, & Lambon Ralph, 2006a; Patterson, Graham, & Hodges, 1994), and other frameworks anticipating a more indirect link in which there are separable yet interacting processes (e.g., Hulme et al., 1997; Saint-Aubin & Poirier, 1999, 2000). Both long-term lexical representations of the phonological sequences that correspond to real words, and semantic representations that allow these word forms to be associated with meaning, contribute to the ISR advantage seen for words relative to nonwords (Hoffman, Jefferies, Ehsan, Jones, et al., 2009; Hulme, Maughan, & Brown, 1991; Hulme, Roodenrys, & Brown, 1995; Jefferies, Frankish, et al., 2006a; Jefferies, Frankish, & Lambon Ralph, 2006b; Majerus & van der Linden, 2003; Saint-Aubin & Poirier, 1999, 2000; Thorn, Gathercole, & Frankish, 2005). However, these theoretical positions also make different predictions about the relevance of brain

regions that support heteromodal concepts, with some accounts suggesting these are critical to verbal STM, and others proposing that the semantic influence in verbal STM is played out within a language system that is distinct from non-verbal concepts that allow us to recognise objects and understand and produce actions (e.g., Papagno, Vernice, & Cecchetto, 2013; Patterson et al., 2006).

Many neuropsychological studies have supported a distinction between semantic processing in temporal lobe regions and phonological processing in temporoparietal junction and inferior parietal cortex (e.g., Alexander, Hospital, & Street, 1992; Hodges, Patterson, Oxbury, & Funnell, 1992; Jefferies, Jones, Bateman, & Lambon Ralph, 2005; Lambon Ralph, Cipolotti, Manes, & Patterson, 2010; R. C. Martin et al., 1994; Price et al., 2003; Sakurai et al., 1998; Shallice & Warrington, 1974; Warrington, 1975; Warrington & Shallice, 1969; Wilshire & Fisher, 2004). These observations, combined with the importance of both semantic and phonological abilities to verbal short-term memory, predict that there should be qualitatively different patterns of verbal STM deficits following lesions within these brain areas. While this hypothesis is broadly supported by neuropsychology, here we test the prediction using inhibitory off-line transcranial magnetic stimulation (TMS) in healthy participants. This approach has some unique advantages: it licences causal inferences, like neuropsychology, yet allows relatively focal inferences about specific brain regions in the absence of confounding factors. We target regions implicated in phonological processing (left supramarginal gyrus, SMG) and heteromodal conceptual knowledge (left anterior temporal lobe, ATL), with more precision than would be possible in patients with large lesions or neurodegenerative disease. Moreover, we apply TMS to these different regions within the same participants, eliminating confounds operating at the level of the individual. In contrast, our earlier case-series comparisons of verbal STM in patients with semantic dementia and phonological dyslexia following stroke aphasia (Jefferies, Crisp, et al., 2006) had the disadvantage of comparing patients with different aetiologies (although the advantage of investigating participants with deficits largely restricted to the relevant cognitive domain): in these circumstances it is hard to exclude the effect of confounding factors resulting from the comparison of neurodegeneration and cardiovascular accident.

While there are also studies focussed on semantic and phonological deficits specifically in stroke patients (N. Martin & Saffran, 1997; Verhaegen et al., 2013), stroke rarely causes lesions to ATL, since this is a

watershed region supplied by both middle cerebral artery and the anterior temporal branch of the posterior cerebral artery (Phan, Donnan, Wright, & Reutens, 2005; Phan, Fong, Donnan, & Reutens, 2007). Consequently, studies of stroke aphasia are not well-suited to investigating the functional significance of ATL. This highlights a key advantage of TMS: it can be applied to theoretically-significant sites, instead of requiring naturally-occurring lesions. In addition, stroke tends to cause significant damage to white matter damage, which will make a major contribution to cognitive impairment. In the context of the vasculature of the brain, localising focal regions responsible for specific semantic or phonological impairments due to stroke is complicated since damage will tend to involve other perisylvian, middle cerebral artery territory that could, independently or interactively, underlie the impairment. Thus, methods such as voxel-based lesion-symptom mapping are helpful in identifying common loci of lesions (e.g., Buchsbaum et al., 2011; Kümmerer et al., 2013; Mirman et al., 2015; Schwartz et al., 2009; Schwartz, Faseyitan, Kim, & Coslett, 2012; Walker et al., 2011) but do not necessarily isolate critical function.

In addition to avoiding confounds associated with individual participants, and the capacity to select stimulation sites irrespective of where brain injury and degeneration tends to occur, TMS studies also allow the assessment of a site's functional significance in the absence of any gross language deficits and secondary impairments. In neuropsychological studies, it can be difficult to distinguish the relative contribution of semantic and phonological representations due to the broad impact of aphasia on everyday language usage across domains: for example, words with degraded meaning will also show diminished use of their phonological form (Papagno et al., 2013). These considerations, along with the "lack of 'pure specificity'" of impairments to one type of processing associated with damage (Price, in press), uncertainty and variability regarding premorbid function, and the adjacency of functions with different associated impairments (Humphreys & Lambon Ralph, 2015) limits interpretations of functional specificity based on neuropsychological data. Inhibitory brain stimulation in healthy participants can allow greater spatial resolution while retaining the capacity to draw causal inferences about brain regions that make a necessary contribution to specific aspects of cognition. TMS can thus help to determine whether specific semantic and phonological regions critically contribute to verbal short-term memory function.

Studies applying TMS to modulate verbal short-term memory function to date have tested a range of left-lateralised language-related sites (inferior and superior parietal, lateral prefrontal, premotor, mid- and posterior-temporal) but have predominantly assessed response times in probe recognition tasks (Deschamps, Baum, & Gracco, 2014; Düzel, Hufnagel, Helmstaedter, & Elger, 1996; Herwig et al., 2003; Kirschen, Davis-Ratner, Jerde, Schraedley-Desmond, & Desmond, 2006; Liao, Kronemer, Yau, Desmond, & Marvel, 2014; Mottaghy et al., 2000; Mottaghy, Gangitano, Krause, & Pascual-Leone, 2003; Nixon, Lazarova, Hodinott-Hill, Gough, & Passingham, 2004; Postle et al., 2006; Romero Lauro, Walsh, & Papagno, 2006; Romero Lauro, Reis, Cohen, Cecchetto, & Papagno, 2010). While these tasks have helped to identify candidate sites contributing to the storage, rehearsal or manipulation of verbal material, they primarily place demands on order memory rather than item memory (in these button press tasks, items are often drawn repeatedly from a small set of items, such as digits or letters, and therefore the task is to verify the presence of familiar items at a given position in a sequence), and thus offer little in the way of insight regarding the nature of support from long-term representations of individual items in STM. TMS studies that have examined effects on short-term verbal recall of items have focused on either limited set of words (e.g., free recall of a single 12 word list per TMS condition, Grafman et al., 1994) or delayed recall of unfamiliar nonwords (Acheson, Hamidi, Binder, & Postle, 2011). This latter TMS study examined relationships between STM function and broader language processing: Acheson et al. (2011) localised stimulation sites in left posterior superior temporal gyrus (pSTG) and posterior middle temporal gyrus (pMTG), on the basis of their contribution to phonological encoding and lexical-semantic retrieval outside of a STM context (guided by fMRI activation in nonword reading and picture naming tasks, respectively). They found that fewer nonwords were produced as a consequence of pSTG stimulation, relative to pMTG stimulation or no TMS. Furthermore, disruption to the phonological site affected a non-STM task, paced reading (and slowed picture naming latencies, but to a lesser extent than disruption of the lexical-semantic pMTG site). Accordingly, the authors (Acheson et al., 2011; Acheson & MacDonald, 2009) proposed that our ability to briefly maintain an unfamiliar sequence of speech sounds causally depends on the same phonological encoding and articulatory planning systems involved in language production, with nonword maintenance drawing upon temporary activation of long-term phonological representations. An untested

implication of this study is that disruption of the lexical-semantic site would diminish the benefits of long-term lexical-semantic representations for familiar words (relative to unfamiliar nonwords) in STM.

The present study tested the prediction that inhibitory TMS to phonological and semantic sites would differentially disrupt STM for nonwords and words respectively. This pattern is seen in patients with phonological or semantic deficits and is predicted by language-based accounts of STM. Our choice of brain stimulation sites was guided by studies which have previously used TMS to successfully modulate phonological or semantic performance outside of a STM context, as well as the locations of brain injury in patients with phonological and semantic deficits (in the context of stroke aphasia and semantic dementia). Left supramarginal gyrus (SMG) was selected as a phonological site given the sensitivity of phonological task performance to TMS disruption here (Pattamadilok, Knierim, Duncan, & Devlin, 2010; Romero Lauro et al., 2010, 2006; Sliwinska, James, & Devlin, 2015; Sliwinska, Khadilkar, Campbell-Ratcliffe, Quevenco, & Devlin, 2012). The left inferior parietal region, incorporating our target site within SMG, has been widely linked to verbal maintenance and phonological processing more generally (Henson, Burgess, & Frith, 2000; R. C. Martin, Wu, Freedman, Jackson, & Lesch, 2003; Paulesu et al., 1996; Paulesu, Frith, & Frackowiak, 1993; Salmon et al., 1996; Vallar et al., 1997). Neuropsychological and functional imaging evidence implicate SMG involvement in more abstract, heteromodal phonological and speech perception/production tasks (Baldo, Katseff, & Dronkers, 2012; Booth et al., 2003; Fridriksson et al., 2010; Herman, Houde, Vinogradov, & Nagarajan, 2013; Kemeny et al., 2006; Moser, Baker, Sanchez, Rorden, & Fridriksson, 2009; Newman & Twieg, 2001; Oberhuber et al., 2016; Papoutsi et al., 2009; Parker Jones et al., 2014; Pilkington et al., 2017; Raizada & Poldrack, 2007; Shuster & Lemieux, 2005; Tomasino et al., 2015; Turkeltaub & Branch Coslett, 2010), including tasks with minimal maintenance demands (e.g., Booth et al., 2002; Celsis et al., 1999; Church, Balota, Petersen, & Schlaggar, 2011; Gold & Buckner, 2002; Liebenthal, Sabri, Beardsley, Mangalathu-Arumana, & Desai, 2013; Oberhuber et al., 2016; Peramunage, Blumstein, Myers, Goldrick, & Baese-Berk, 2011; Prabhakaran et al., 2006; Wilson, Isenberg, & Hickok, 2009; see also Lorca-Puls et al., 2017). It has been suggested that SMG's involvement in STM might primarily be an index of phonological linguistic processing requirements rather than STM load (Buchsbaum & Esposito, 2008; Majerus et al., 2012; Ravizza, Delgado, Chein, Becker, & Fiez, 2004). SMG is

strongly implicated in the process of mapping between orthographic (written) codes and phonological codes (cf., Price, 2012), and between acoustic and articulatory motor codes (Corina et al., 2010; Hickok & Poeppel, 2007; Rauschecker & Scott, 2009). On the basis of this literature on SMG and its implication in processing syllable/word-level phonological form, we predicted that TMS to this region would impair both word and nonword recall in a verbal STM task, but affect nonword recall to a greater extent since nonword maintenance relies entirely upon temporary acoustic-to-motor activation (i.e., without available supportive activation of long-term lexical-semantic representations).

Our second stimulation site, left ATL, is not implicated in phonological processing. Neither is it implicated in lexical-level knowledge (which is associated with more posterior temporal regions: Gow, 2012; Graves, Grabowski, Mehta, & Gupta, 2008; Hickok & Poeppel, 2007). Instead, converging evidence from neuropsychology, neuroimaging and brain stimulation shows that this site is critical for heteromodal semantic memory (Coutanche & Thompson-Schill, 2015; Lambon Ralph et al., 2016; Pobric, Jefferies, & Lambon Ralph, 2010a; Visser, Jefferies, Embleton, & Lambon Ralph, 2012). Patients with semantic dementia have relatively focal atrophy of anterior temporal (ATL) cortex which correlates with progressive semantic impairment across verbal and non-verbal tasks (Mion et al., 2010; Mummery et al., 2000; Patterson, Nestor, Rogers, & Nestor, 2007). Other aspects of cognition, including phonological and verbal STM for nonwords and numbers processing, are largely spared (Jefferies et al., 2005; Jefferies, Patterson, Jones, Bateman, & Lambon Ralph, 2004; Majerus et al., 2007). However, patients with semantic dementia do show some impairment of verbal STM for words that have become semantically degraded, suggesting that semantic activation contributes to the capacity to maintain phonological sequences in STM (Jefferies et al., 2008; Knott, Patterson, & Hodges, 1997; Patterson et al., 1994). While effects of semantic variables are often seen in STM, it remains controversial the extent to which semantic support can be considered independently from lexical variables such as word usage or co-occurrence (Benetello, Cecchetto, & Papagno, 2015; Papagno et al., 2013). We have provided some compatible experimental evidence for interactions between semantic and phonological properties in STM in healthy individuals, suggestive of direct effects on phonological maintenance (Savill et al., 2018; Savill, Ellis, & Jefferies, 2017; Savill, Metcalfe, Ellis, & Jefferies, 2015), but these studies do not rule out differences emerging

in an indirect manner (for example, condition-related attentional or strategic differences at encoding or retrieval). Therefore, one of our key objectives was to examine whether reduced lexicality effects might be replicated in healthy individuals after selective interference with a key semantic site.

Previous studies applying TMS to a similar unilateral, left ATL site have elicited temporary disruption of performance in a range of semantic tasks in healthy individuals (Binney & Lambon Ralph, 2015; Hoffman & Crutch, 2016; Jackson, Lambon Ralph, & Pobric, 2015; Lambon Ralph, Pobric, & Jefferies, 2009; Pobric, Jefferies, & Lambon Ralph, 2007, 2010b; Pobric et al., 2010a; Pobric, Lambon Ralph, & Jefferies, 2009), in line with this region's implication in heteromodal conceptual knowledge/semantic representation (see Lambon Ralph, Jefferies, Patterson, & Rogers, 2016, for a recent review). Indeed, although ATL atrophy in SD is bilateral and semantic memory is thought to be bilaterally represented (Lambon Ralph et al., 2016; Patterson et al., 2007), observations of asymmetries in atrophy and function strongly indicate that the left ATL has a more important role than the right in tasks requiring semantically driven speech production (Woollams & Patterson, in press)[1], which suggests it should be a good candidate site to test. Thus, we could determine whether inhibitory TMS to this semantic site would interfere with the STM advantage normally seen for words relative to nonwords.

This study is the first to (1) investigate the effects of inhibitory TMS on immediate serial recall (ISR) using spoken presentation and recall measures, which have not been used commonly in cognitive neuroscience; (2) use TMS to examine the contribution of long-term representations to STM performance (i.e., by assessing the effects of stimulation on the lexicality effect in this task); and (3) consider the impact of modulation of left ATL function in healthy individuals on STM. By testing spoken verbal recall (rather than, for example, a probe recognition task) and by using an unlimited set of word and nonword stimuli (rather than a restricted set of items), our study is well-placed to examine the mechanisms that maintain item identity in STM. Furthermore, by avoiding visual presentation of verbal stimuli, we eliminate any potential effects of

[1] There is some debate whether the left ATL's greater role in verbal semantic tasks than the right ATL reflects the connectivity of heteromodal representations within left ATL with a left lateralised, pre-semantic language system (Patterson et al., 2007) or due to the left hemisphere being responsible for language-mediated semantic representations (Gainotti, 2015). In either case there is ample evidence for this verbal/nonverbal asymmetry in semantic performance between left and right ATL.

disruption to orthographic-phonological mapping processes, also linked to SMG (e.g., Stoeckel, Gough, Watkins, & Devlin, 2009). The spoken context privileges phonological access (Baddeley, 1986) and accordingly affords a relatively pure test of phonological buffering capacities. As such, our task provides a robust test of any semantic influences on verbal STM.

Given the limited number of experimental trials that can be tested under TMS conditions within a single session, plus marked individual differences in both ISR and the effects of stimulation, we compared the recall of test lists calibrated to each individual's word and nonword spans and in relation to performance in a non-TMS baseline ISR task within each session. We controlled for residual variation in list difficulty and individual performance with linear mixed effects modelling. Furthermore, we included a visual pattern memory control task to identify possible non-specific effects of TMS. Due to its role in phonological processing, we expected stimulation of SMG to disrupt verbal STM, and particularly impact recall of nonword items that are not supported by long-term word-level representations. If semantic activation does not make a necessary contribution to STM, then TMS to ATL should not impact ISR; if, on the other hand, stimulation of ATL is sufficient to impact recall, we would expect this effect to be specific to words. A dissociation in the effects of TMS to SMG and ATL would be consistent with language-based accounts of verbal STM.

Method

Study Overview

The study employed a within-subjects design, allowing us to compare auditory-verbal serial recall performance for lexical-semantic stimuli (nouns) and non-lexical, phonological material (nonwords) with and without the effects of stimulation, applied to a site linked to phonological processing (left supramarginal gyrus) and a site linked to semantic but not phonological processing (left anterior temporal lobe). Participants performed the verbal short-term memory task immediately after stimulation with a low-frequency (1 Hz) ten-minute inhibitory train of rTMS pulses offline. In this 'offline' method, when TMS pulses are applied repeatedly at a low frequency, the effects last beyond the end of the stimulation period (for approximately the period of stimulation, e.g., Chen et al., 1997), allowing us to test effects on recall performance without any disrupting

influence from the loud clicks, jaw contractions, or eye blinks following peripheral nerve stimulation associated with each stimulation pulse. Participants performed the baseline testing (i.e., without TMS) either before TMS stimulation or ~35 min after TMS stimulation (25 minutes after completing the TMS experiment; by which time, the effects should no longer be present: Lambon Ralph et al., 2009; Pobric et al., 2007, 2009; Whitney, Kirk, O'Sullivan, Lambon Ralph, & Jefferies, 2011). The order of baseline testing was counterbalanced across sessions for each participant. The study also made use of a non-linguistic visual pattern memory control task (an electronic variant of the pattern span task used to assess visuo-spatial memory, adapted from Della Sala, Gray, Baddeley, Allamano, & Wilson, 1999) to characterise any non-specific effects of TMS. With this principled TMS approach (by testing for dissociations), we minimised the stimulation demands on our participants and dispensed with the need for active control sites, which have been questioned on ethical grounds (Davis, Gold, Pascual-leone, & Bracewell, 2013). The two stimulation sites were tested in separate sessions; for any given participant, these sessions took place at the same time of day at least seven days apart. Prior to the first TMS session, participants were individually tested on their verbal recall span for lists of words, lists of nonwords and their visual memory span. Experimental list lengths were set to span plus one item for word and nonword lists (or one grid-size above span for the visual STM task), to maximise sensitivity to the effects of TMS. In each session, there were two testing phases lasting less than 10 minutes, in the TMS-free baseline period and directly after TMS.

Participants

Participants were 24 native British English students from the University of York (aged between 19 and 35 years; 12 males), screened for contraindications for receiving TMS. This sample size was determined by our counterbalancing requirements (which required a multiple of 12) and our previous observation of significant stimulation effects on immediate serial recall from transcranial direct current stimulation (tDCS) in a sample of 24 participants (Savill, Ashton, et al., 2015). The current sample is one of the largest for this field: of the 12 TMS studies on verbal short-term memory cited here, only two included a larger sample size and the mean N is 15. We excluded and replaced two participants who were not native speakers of British English, two who had

significantly different baseline performances and one who chose to withdraw after the first TMS session[2]. All participants were right-handed with normal hearing and normal or corrected-to-normal vision, and were reimbursed £20 for their time. Each participant gave their informed consent before each TMS testing session, and the experiment was reviewed and approved by the research ethics committee of the York Neuroimaging Centre.

Stimuli

Word and Nonword List Stimuli.

Eight-item test lists for immediate serial recall were designed to accommodate possible high spans. Two open sets of twenty word lists and twenty nonword ISR lists, for use before and after TMS were created (i.e., stimuli appeared once within a session). Lists comprised unrelated CVC items, such that no phoneme was repeated within a given syllable position in the list, and word lists (all nouns) were constructed to ensure they were matched for their averaged properties of lexical frequency (Set A *M* = 4.13, *SD* = 0.22; Set B *M* = 4.09, *SD* =0.23; according to SUBTLEX, van Heuven, Mandera, Keuleers, & Brysbaert, 2014), imageability (Set A *M* = 5.67, *SD* = 0.33; Set B *M* = 5.69, *SD* =0.29; according to Cortese & Fugett, 2004) and AoA (Set A *M* = 6.30, *SD* = 0.22; Set B *M* = 6.45, *SD* =0.66; according to Kuperman, Stadthagen-Gonzalez, & Brysbaert, 2012). Nonword lists were created by recombining the phonemes of word lists and so that they sounded like plausible 'English' words (rather than phonologically-odd) (e.g., the word list 'bus /bʌs/, note /nəʊt/, patch /pætʃ/, hawk /hɔk/, yell /jel/, roof /ruf/, game /geɪm/, dish /dɪʃ/' became the nonword list 'putch /pʌtʃ/, hoce /həʊs/, yal /jæl/, norb /nɔb/, ket /ket/, roosh /ruʃ/, gim /gɪm/, dafe /deɪf/'). This design tactic can be considered successful since there were no differences in summed biphone probability between the final set of words and nonwords (words *M* = .006; nonwords *M* = .006; $t(638) = 0.81$, $p = .42$) (calculated using the Phonotactic Probability Calculator; Vitevitch & Luce, 2004). Stimuli were recorded by a female British English speaker and edited to 750 ms in length, with background noise removed and average intensity controlled using Praat (www.praat.org).

[2] Our 24 participants comprise the final group of participants whose data were fully transcribed and analysed.

Visual Memory task stimuli.

We used a pattern STM task that required participants to temporarily store and reproduce visual patterns (similar to Della Sala et al., 1999). The stimuli were square and rectangular arrays of cells (3×3, 4×4, 5×5, 6×6, 7×7; 3×4, 4×5, 5×6, 6×7) (each sized 5 × 6 cm), in which half of the cells were white and the remainder were black. To minimise response time associated with the reproduction of different visual patterns, participants were presented with partially-filled grids to complete: Two non-contiguous black cells from each probe pattern array were changed to white for test trials; two mouse clicks were permitted per trial. Forty unique pattern arrays were developed for each grid size (10 for each TMS and baseline session) and a further four of each size were developed for the span task to determine each participant's grid size for the TMS experiment.

Procedure

Span Testing.

Prior to the first TMS session, participants' word, nonword, and pattern spans were assessed. ISR lists of increasing length (four lists per length, from three to eight monosyllabic items; not used in the main experiment) were auditorily presented and word and nonword spans were each determined as the final length that at least two of four lists were recalled completely correctly. Pattern span was similarly tested: In the span test, four trials of each grid size were tested, increasing in size over time; span was determined as the final grid size that both of the two missing cells were correctly clicked in at least two of the four trials and test size was set to the next size up. Span+1 sizes ranged from 5-7 for words, 4-5 for nonwords and from 5×5-6×7 matrices for visual patterns.

Localisation of Stimulation Sites.

Structural T1-weighted MRI scans (TR = 7.8 ms, TE = minimum full, flip angle 20°, matrix size = 256 × 256, 176 slices, voxel size = 1.13 × 1.13 × 1 mm^3) were used to anatomically identify lateral sites for stimulation in each participant's brain. Each individual anatomical image was overlaid on the MNI template and the subject-specific stimulation site was marked. The individual sites are plotted in Figure 1.

SMG targets were identified rostral to the posterior ascending ramus of the lateral fissure, in the left ventral anterior supramarginal gyrus (average MNI coordinate = -53, -37, 25). This particular location was targeted on the basis of previous demonstrations of its sensitivity to TMS disruption of phonological task performance (e.g., Pattamadilok et al., 2010; Romero Lauro et al., 2010, 2006, Sliwinska et al., 2015, 2012) and fMRI evidence of its involvement in heteromodal phonological and speech production tasks, including tasks with minimal maintenance demands (e.g., Booth et al., 2002; Oberhuber et al., 2016; see also Lorca-Puls et al., 2017).

ATL target sites were localised following Pobric, Lambon Ralph, & Jefferies (2009); an individual's ATL site was selected approximately 1 cm in from the tip of the temporal pole, along the left middle temporal gyrus (average MNI coordinate = -52, 0, -23). Previous studies found that inhibitory TMS to this site disrupted semantic performance (Binney & Lambon Ralph, 2015; Jackson, Lambon Ralph, et al., 2015; Lambon Ralph et al., 2009; Pobric et al., 2007, 2010b, 2010a, 2009) and fMRI evidence shows semantic activation (Hoffman, Binney, & Lambon Ralph, 2015).

To verify the functional distinctiveness of our two stimulation sites, we entered the average coordinates for each stimulation site in Neurosynth (Yarkoni, Poldrack, & Nichols, 2011) to generate functional connectivity maps. We identified distinct patterns of functional connectivity related to motor control/imagery for SMG and semantic memory for ATL (See Figure 1).

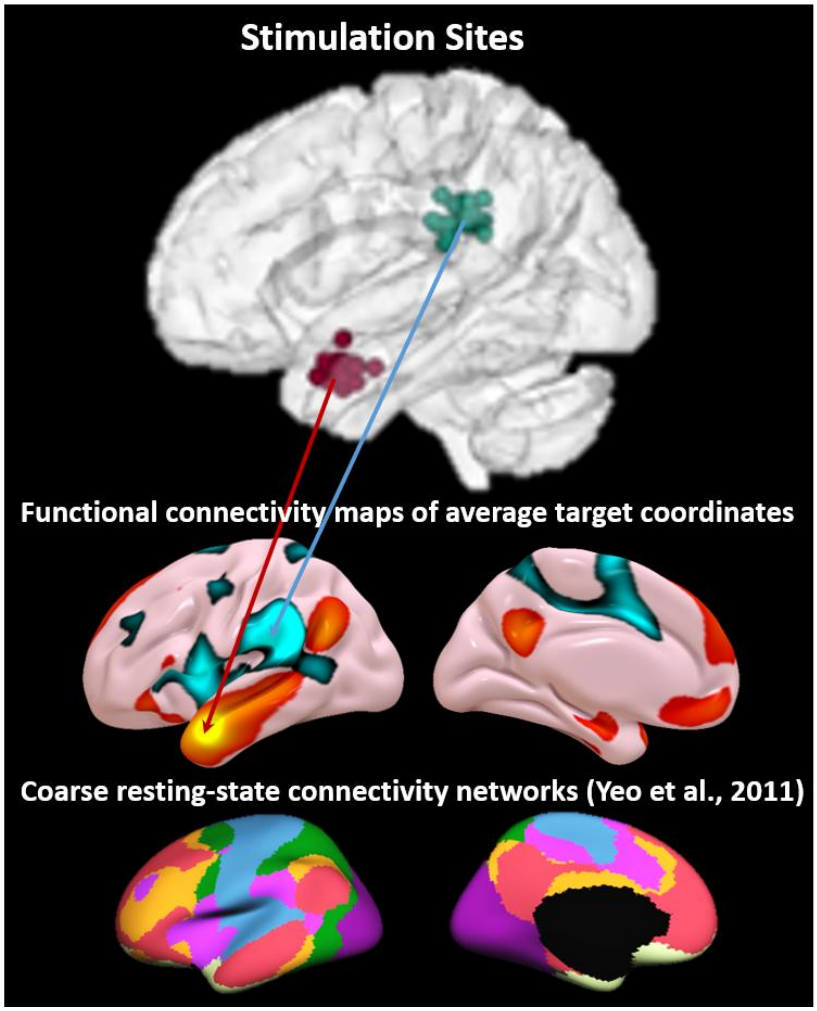

Figure 1. A glass brain (top) plotting the MNI coordinates of the individual anatomically localised stimulation sites within left supramarginal gyrus (SMG; cyan) and anterior temporal lobe (ATL; red). Functional connectivity maps for the average stimulation sites in Neurosynth (Yarkoni et al., 2011) identified distinct patterns of functional connectivity for SMG and ATL (middle panel). Comparison with the resting-state networks identified by Yeo et al. (2011; bottom panel) revealed that SMG's pattern of intrinsic connectivity resembled the ventral attention network, and included auditory-motor regions (shown in violet), while ATL's pattern of intrinsic connectivity overlapped with the default mode network, implicated in memory (shown in red).

The 'Brainsight' frameless stereotaxy system was used to co-register the identified site within SMG and ATL to the participant's head. Four landmarks were used to co-register each participant's head to their brain image using a Polaris infra-red tracking device (i.e., tip of the nose, left/right tragus and nasion).

Transcranial Magnetic Stimulation.

Before TMS testing began, the individual's active motor threshold was established in each testing session. This was determined by the lowest stimulation intensity required to elicit visible contraction of the first

dorsal interosseous muscle in the contralateral hand. Motor thresholds ranged between 38% and 65% of maximum stimulator output, with an average of 49% of stimulator output. A 70-mm figure-of-eight coil, attached to a MagStim Rapid2 stimulator, was used to deliver the magnetic pulses. Repetitive trains of TMS were applied at 1 Hz for 10 min; participants were stimulated at 120% of their active motor threshold.

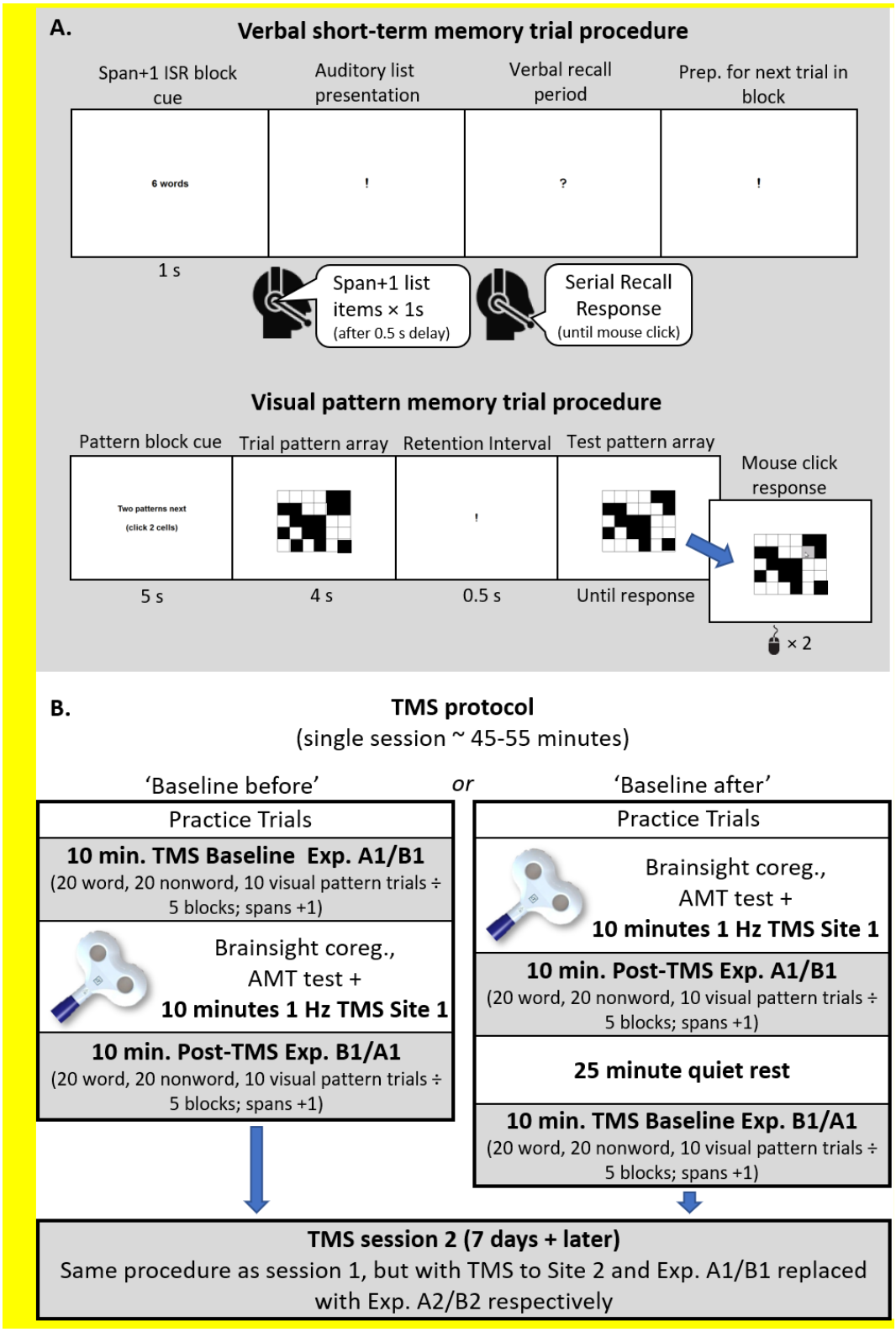

Figure 2. TMS Experimental Protocol. (A) The structure of an individual verbal short-term memory trial and a visual pattern memory control trial in the TMS Experiment. The procedure for word and nonword verbal short-term memory trials differed only in the number of list items presented and in the initial block cue detailing the number and type of items in the upcoming lists. The visual display over the course of a verbal short-term memory trial is shown above the concurrent auditory components of the task. Participants were instructed to try to verbally recall all the trial's list items in the order

that they had been presented at the end of each list, identified by a question mark on screen. In visual pattern memory trials, participants were instructed to use the mouse to click the two white cells in the test pattern array that were black in the trial pattern array. For all trials, the block cue screen appeared at the beginning of a block (consisting of either four word list trials, four nonword trials, or two pattern memory trials). This screen had a longer display period at the start of pattern trials to accommodate adjustment to the switch in input modality and task demands. Within a block, a 0.5 s preparation screen (exclamation mark fixation) preceded the onset of stimulus presentation in the next trial, following a trial-end mouse-click. (B). Structure of a single TMS session. Different experimental sets were used to test performance in the baseline and post-TMS phases. ISR stimuli were reordered within their sets for the second session to form new lists, such that each item was heard at most, once more a week later.

Experimental Procedure.

The procedure was identical for both TMS sessions (see Figure 2). A PC running E-Prime software (Psychology Tools, Inc., Pittsburgh, PA) was used to present the experiment. Experimental trials were set to span+1 size, as determined in prior span testing. Both versions of the ISR task, for use with TMS and in the baseline task, contained twenty word lists, twenty nonword lists and ten pattern trials (in blocks of four word lists, four nonword lists, followed by two pattern trials, or four nonword lists, four word lists followed by two pattern trials). Participants wore a headset with in-built microphone to listen to and recall the lists. At the beginning of a word or nonword block of trials, a screen reminded participants of the type of list and number of items (e.g., '6 words' or '5 nonwords') that were coming up. An exclamation mark was displayed on screen from 250 ms prior to the onset of the first item until the offset of the final item in a list. Items were presented at a rate of 1 s per item. At the end of the presented list, a question mark appeared, which acted as the cue to verbally recall the items in serial order (see Figure 2). Participants pressed a key to indicate when they had finished recalling a list, which prompted the next trial. Participants were asked to recall items in the order in which they were presented and to attempt recall all items, even if unsure. Pattern memory trials were prompted by a display for five seconds ('Two patterns next (click two cells)'). Patterns were displayed for four seconds, and after a 0.5 s interval with an exclamation mark display, the test array was displayed and stayed on screen until two mouse clicks had been registered. Cells briefly changed in colour to grey to acknowledge cell clicks. Participants had been instructed to click the two cells that had changed from black to white. They had

two practice trials of each trial type to familiarise themselves with the task. Verbal responses were digitally recorded.

Transcription.

Verbal responses were transcribed phoneme-by-phoneme. We adapted the coding scheme used by Savill, Metcalfe, Ellis, & Jefferies (2015) to accommodate different list lengths. Coding focused on whether list items were recalled, either in the correct or incorrect position, or not. We also recorded the category of response error types according to the criteria used by Savill, Metcalfe, et al. (2015).

Data Analysis

The ISR and visual pattern memory control task data were analysed separately.

ISR data analysis.

To control for variability across individual participants in overall performance and the effects of TMS (e.g., due to skull thickness; anatomical variability) and account for fluctuations in the linguistic properties of individual ISR lists on our recall measures, we applied linear mixed effects modelling to the recall accuracy data. We used PROC MIXED (SAS v9.4, SAS Institute, North Carolina, USA) to build a logistic generalized linear mixed model to predict the recall data for each participant for each ISR test item (whether the item was recalled in position or not – i.e., a binary distribution, using a logit link function). This analysis approach accounts for interdependence of the data arising from repeated measurements of the same participants and adjusts for non-normal distributions (Baayen, Davidson, & Bates, 2008; Dixon, 2008). Fixed effects included stimulation site (ATL versus SMG), TMS (no-stimulation baseline versus post-TMS), lexicality (words vs. nonwords), test list size (4, 5, 6 or 7) and the serial position of the item in the list as fixed effects. In addition, we included the three-way interaction between site, TMS and lexicality, which allowed us to generate the planned comparisons required to test our hypotheses. To prevent over-fitting, other interaction terms were only included if they significantly improved model fit, assessed via a significant reduction in -2 Log-likelihood: the critical three-way interaction did improve model fit but no other 2-way or 3-way interaction terms did so. Consequently, the final model included the five fixed effects and this single interaction term. -2 Log-likelihood was 22162.1 for the empty model, 21206.8 for the final model, and 21211.27 for the final model minus the three-way interaction

term. The Pearson chi-square by degrees of freedom was 0.98, suggesting there was no over-dispersion in the fitted model. We permitted individual intercept variation for each subject and item as random effects and specified an 'unstructured' variance–covariance structure for the G-matrix in the model. Two participants who showed blanket facilitation following TMS were excluded from further analysis: they were alone in failing to show any disruptive effects of TMS for either words or nonwords (i.e., numerically poorer), following either SMG or ATL stimulation.

Four planned comparisons, corrected for multiple comparisons within the GLIMMIX procedure, checked for significant effects of TMS on ISR performance: These compared differences between the baseline and TMS conditions in the recall of words and nonwords for both sites (e.g., nonwords SMG baseline vs nonwords SMG TMS). Descriptive (unmodelled) data are also provided for different response categories to characterise any effects of TMS on error types.

Visual pattern memory control task data analysis.

Similar to the ISR analysis, we used PROC MIXED (SAS v9.4, SAS Institute, North Carolina, USA) to build a logistic generalized linear mixed model to predict the pattern completion accuracy data for each participant for each pattern trial (whether the pattern was correctly recalled or not – i.e., a binary distribution, using a logit link function). Fixed effects included stimulation site (ATL versus SMG), TMS (no-stimulation baseline versus post-TMS), grid array size (5×5, 5×6, 6×6, or 6×7) and trial number in session (1-10) as fixed effects. We included the two-way interaction between site and TMS. To prevent over-fitting, other terms were only included if they significantly improved model fit, assessed via a significant reduction in -2 Log-likelihood. To succinctly capture a non-linear effect of trial number, the final model consequently included the four fixed effects, along with trial number included as a continuous variable with second and third order polynomial terms and the single interaction term of TMS x site. -2 Log-likelihood was 1154.86 for the empty model and 1138.79 for the final model, and 1138.98 for the final model minus the two-way interaction term. The Pearson chi-square by degrees of freedom was 0.96 suggesting there was no over-dispersion in the fitted model. We permitted individual intercept variation for each subject and item as random effects and specified an 'unstructured' variance–covariance structure for the G-matrix in the model. The two participants who had been excluded in

the previous analysis for showing blanket facilitation following TMS were excluded in this analysis, also.

Planned comparisons assessed the TMS effect on LS Mean pattern recall probability according to site.

Results

ISR Results

The modelled mean probability of items recalled in position for each TMS condition and the average TMS effect scores are displayed in Figure 3.

Figure 3. Performance in the immediate serial recall (ISR) task (left) and the control visual pattern memory task (right). The bar graphs in the top panels show modelled mean performance (Least Squares Means) in each condition. Error bars = +/-1 standard error of the mean (SEM). The bottom panel shows average *changes* in recall performance following TMS compared to baseline, for nonwords and words in the ISR task and across trials in the pattern memory control task. These

data are expressed as odds ratios, since in a logistic model, the effect of TMS can be characterised in terms of changes in the probability that a particular item or pattern will be recalled. Changes in odds ratios larger than one (1 = no change from pre to post-TMS; dotted lines are provided for reference) correspond to greater TMS effects (i.e., more disruption in performance). Error bars = 95% confidence intervals. In ISR, the effect of SMG stimulation on nonword recall was the most statistically-robust effect; the effect of SMG stimulation on words was close to significance. The effect of ATL stimulation on word recall was also significant, while stimulation of this semantic site had no effect on nonword recall. In the pattern memory task, stimulation to neither site disrupted performance.

Table 1. *Details of the statistical model used to estimate the recall of words and nonwords before and after TMS was applied to supramarginal gyrus and anterior temporal lobe.*

Model Parameters	F-value (DF)	Z-value	p-value	Parameter Estimate	Parameter 95% CI	-2Log likelihood
Empty Model						22162.1
Full Model						21206.8
Fixed Effects						
Site (ATL, SMG)	1.98 (1, 17776)		.20	-0.01	-0.13 – 0.12	
Item (WD, NW)	363.93 (1, 17776)		<.001	-2.29	-2.54 – -2.03	
TMS (PRE, POST)	13.16 (1, 17776)		<.001	0.11	-0.02 – 0.23	
Site*Stim*TMS	4.43 (4, 17776)		.40	1) 0.12	-0.14 – 0.39	
				2) 0.12	-0.08 – 0.31	
				3) 0.19	-0.06 – 0.38	
				4) 0.03	-0.15 – 0.21	
Item position in list	623.01 (1, 17776)		<.001	-0.36	-0.39 – -0.33	
List size	111.71 (1, 17776)		<.001	-0.58	-0.68 – -0.47	
Random Effects						
Subject covariance		3.26	<.001	0.58		
Item covariance		11.45	<.001	0.49		

Note. The table shows the fixed and random effects in the final model used to generate planned comparisons examining the effect of TMS on the recall of words and nonwords for each site. Only fixed effects that significantly improved model fit were included: the three-way interaction, while not significant overall, did improve model fit. Site: Anterior temporal lobe (ATL) vs. Supramarginal gyrus (SMG). Item: words (WD) vs. nonwords (NW). TMS: performance at no-TMS baseline (PRE) and post-TMS (POST). For dummy variable coding, the control levels were SMG for site, words for item type and POST for TMS.

Since our focus was on a hypothesised double dissociation between ATL and SMG, we built a mixed-effects model that allowed us to compare performance before and after inhibitory stimulation was applied to these two sites. Planned comparisons of least-squares means, comparing pre- and post-TMS sessions for words

and nonwords, were consistent with our predictions: SMG stimulation significantly disrupted nonword recall: $t(17776) = 2.98$, $p = .003$, while the effect for words was not significant ($t(17776) = 1.64$, $p = .101$). The opposite pattern was found for ATL, although these effects were more subtle: stimulation to this semantic site significantly disrupted word recall: $t(17776) = 2.08$, $p = .038$, while nonword performance was not significantly affected ($t < 1$). Full details of the model are provided in Table 1.

Descriptive data on the nature of errors in each TMS condition are provided in Table 2. In brief, these categorical data indicate that the dissociation across sites seen in the effect of TMS on overall item recall largely related to changes in the percentage of items recalled in the correct position; and changes in phonologically related errors, notably an increase in phoneme recombination errors in the nonword list condition following SMG stimulation.

Table 2. *ISR response types as a percentage of total test items.*

	Nonword List Condition				Word List Condition			
	ATL Session		SMG Session		ATL Session		SMG Session	
	Baseline	TMS	Baseline	TMS	Baseline	TMS	Baseline	TMS
Item recalled in position (used in LME)	**47.01 (19.49)**	**46.98 (18.63)**	**47.74 (17.81)**	**43.26 (16.84)**	**64.27 (14.97)**	**62.99 (15.39)**	**63.84 (12.98)**	**62.55 (13.68)**
Item recalled out of position	**0.88 (1.13)**	**1.26 (1.90)**	**1.00 (0.88)**	**0.89 (1.30)**	**7.04 (5.57)**	**7.36 (5.07)**	**7.91 (4.99)**	**7.07 (5.22)**
Item Omission	0.57 (1.25)	0.57 (1.85)	0.54 (1.26)	0.18 (0.50)	5.44 (7.04)	6.44 (8.01)	6.07 (6.48)	7.79 (7.31)
Phoneme Recombination Error	24.99 (10.45)	25.10 (10.97)	25.60 (10.62)	28.51 (10.62)	11.62 (6.48)	11.30 (3.29)	10.55 (4.38)	11.05 (3.64)
Phon-related non-recombination error	24.94 (10.11)	24.61 (8.39)	23.91 (7.97)	25.69 (8.15)	9.68 (3.08)	9.77 (4.80)	9.74 (4.91)	10.08 (4.55)
Other (List intrusions/Unrelated)	1.61 (2.16)	1.47 (1.85)	1.21 (1.89)	1.48 (2.35)	1.95 (1.80)	2.14 (1.77)	1.88 (1.81)	1.46 (1.60)

Note. Data show response type as a percentage of target items. Standard deviations are shown in parentheses. Response types shown in bold relate to test items that were recalled; data corresponding to those items recalled in the correct position were fed into our mixed effects modelling analyses.

Visual pattern memory control task results

As expected, TMS did not disrupt recall in the pattern memory task at all. Planned comparisons of least-squares means, comparing pre- and post-TMS sessions for words and nonwords, were consistent with our predictions. Despite adjustments for span that avoided floor and ceiling effects (individual raw correct recall ranged from 15% to 70%), TMS did not significantly alter recall from baseline at either site [SMG: $t(852) = 0.10$, $p = .92$; ATL, $t(852) = 0.71$, $p = .48$]. These results indicate that the disruptive TMS effects on ISR performance cannot be attributed to general effects of TMS.

Table 3. *Details of the statistical model used to estimate pattern recall performance before and after TMS was applied to supramarginal gyrus and anterior temporal lobe.*

Model Parameters	F-value (DF)	Z-value	p-value	Parameter Estimate	Parameter 95% CI	-2Log likelihood
Empty Model						1154.86
Full Model						1138.79
Fixed Effects						
Site (ATL, SMG)	0.08 (1, 852)		.77	-0.02	-0.42 – 0.38	
TMS (PRE, POST)	0.33 (1, 852)		.57	0.02	-0.38 – 0.42	
Site*TMS	0.19 (1, 852)		.67	0.12	-0.44 – 0.69	
Trial number	2.92 (1, 852)		.09	-0.43	-0.93 – 0.06	
Trial number*Trial number	4.17 (1, 852)		.04	0.08	0.003– 0.15	
Trial number*Trial number*Trial number	5.69 (1, 852)		.02	-0.0004	-0.0008 – -0.00008	
Array size	10.27 (1, 852)		.001	-0.08	-0.13 – -0.03	
Random Effects						
Subject covariance		2.45	.007	0.35		

Note. The table shows the fixed and random effects in the final model used to generate planned comparisons examining the effect of TMS on pattern recall for each site. Only fixed effects that significantly improved model fit were included. Site: Anterior temporal lobe (ATL) vs. Supramarginal gyrus (SMG). TMS: performance at no-TMS baseline (PRE) and post-TMS (POST). For dummy variable coding, the control levels were SMG for site and POST for TMS.

Discussion

This study used inhibitory transcranial magnetic stimulation to provide convergent evidence for dissociable neural processes underpinning verbal STM for meaningful and meaningless material. Inhibitory TMS

to left supramarginal gyrus (SMG), implicated in phonological processing, reduced recall of nonword lists. In contrast, stimulation of left anterior temporal lobe (ATL), implicated in heteromodal semantic processing, disrupted word but not nonword recall. For the first time, the study demonstrates that TMS can disrupt a relatively direct marker of verbal STM – namely, the accuracy of spoken immediate serial recall, which is important since most studies have used more indirect measures such as response time for sequence recognition. In this way, our methods are much closer to classical neuropsychological assessments than those typically used in cognitive neuroscience (although unsurprisingly, the effects of TMS in healthy participants were more subtle than the effect of lesions in neuropsychological populations).

Another novel feature of the study is that it contrasted two sites, SMG and ATL, hypothesised to make dissociable contributions to phonological and semantic aspects of language respectively. To our knowledge, this is the first time the effect of inhibitory stimulation to ATL has been assessed using a verbal STM paradigm. Consequently, the study provides highly novel evidence for a necessary role of anterior temporal cortex in the maintenance of familiar meaningful words in healthy participants; since this was the first study of its kind and effects were small, the results should be regarded as preliminary and in need of replication. Nevertheless, the dissociation that we observed between the SMG and ATL sites converges with the patient and neuroimaging literature in suggesting that these distributed brain regions are differentially recruited to support STM depending on the novelty of the individual stimuli and the availability of long-term representations. Patterns of converging evidence are important within cognitive neuroscience because each methodology has limitations which can be overcome through the use of other methods to address the same research question. Unlike neuroimaging studies, neuropsychology allows causal inferences; however, patients typically have large lesions and, depending on the aetiology, both cortical grey matter and the underlying white matter tracts can be affected, potentially eliciting dysfunction at sites that are distant from a focal lesion. Moreover, ATL and SMG are rarely affected in the same way – while SMG is prone to damage from middle cerebral artery stroke, middle and inferior temporal gyrus within ATL are rarely damaged by stroke because these regions have a dual blood supply from both the anterior cerebral artery and the anterior branch of the posterior cerebral artery (Phan et al., 2005, 2007). In this context, TMS studies of healthy participants can make an important contribution to

knowledge, because they can elicit equivalent "virtual lesions" in SMG and ATL. In contrast, neuropsychological studies have rarely compared these sites in the same study, and when they have done so, they have compared patients with stroke affecting SMG with cases who have neurodegeneration affecting ATL in the context of semantic dementia (Jefferies, Crisp, et al., 2006). There are likely to be many important differences between these patients beyond lesion location that are difficult to control within neuropsychological investigations.

Role of left anterior supramarginal gyrus

The SMG finding complements studies that have previously used TMS at this site to disrupt button-press tests of recognition. It is notable that when we use a direct measure of phonological maintenance, we can modulate verbal STM capacity with TMS. Similarly, Acheson et al. (2011) found reductions in nonword recall resulting from stimulation to pSTG (a site implicated in phonological encoding). Here, we show that disruption further along the dorsal pathway (cf. Saur et al., 2008) affects verbal recall capacity for nonwords. ISR is a more direct measure of phonological maintenance than reaction time in STM recognition tasks, given this component of cognition is thought to emerge from the coupling between hearing and speaking. There are no button presses in immediate serial recall to add another source of variance in neural recruitment.

This is a salient consideration for the broader neurobiological literature on STM, since in neuroimaging studies, often for practical reasons such as scanner noise and timing issues related to the use of auditory stimuli, stimuli are visually presented and responses are restricted to a button press (cf. Rottschy et al., 2012, for a summary). The response mode in such studies – and typical use of sub-span numbers of items – places fairly low demands on item memory; instead relative emphasis is given to order recognition. These studies might lack sensitivity to the engagement of lexical-semantic representations to support immediate serial recall. Studies using visual presentation also face some more practical concerns regarding the interpretation of activity changes: There may be difficulties in disentangling STM-related activity in SMG from its role in decoding written words (and confounds with the lexicality advantage of reading familiar words compared to nonwords). Moreover, written presentation might encourage the use of a visual, orthographic code to maintain information.

The few neuroimaging studies that have measured spoken recall have either not found significant SMG activation (e.g., Collette et al., 2001; Grasby et al., 1993; notably Collette et al. did find distinct regions supporting STM for words compared to nonwords) or have interpreted SMG activation primarily in terms of phonological processing/sequencing/attentional demands (e.g., stronger activity for nonwords than words, for words with increasing phonological similarity, for novel vs. overlearned sequences), rather than a storage buffer (Chein & Fiez, 2001; Kalm, Davis, & Norris, 2012; Kalm & Norris, 2014; Logie, Venneri, Della Sala, Redpath, & Marshall, 2003). The greater disruption to the recall of nonwords than words following SMG-TMS could be understood in a similar way. That is, the effects of SMG stimulation on recall could correspond to interference with general/broad phonological processing capacities, rather than specific phonological buffering processes.

A benefit afforded by our silent testing environment, away from scanner noise, is the ability to examine changes in the qualities of recall errors as a consequence of stimulation. Our results indicate that TMS primarily affected whether a target item would be recalled or not (as opposed to a particular category of error). However, we also found tentative evidence, in the case of nonwords, that stimulation of SMG impacted recall by increasing ordering errors at the phoneme level (i.e. increased phoneme recombination errors, which result in fewer items being correctly recalled). This increase is compatible with our SMG stimulation site supporting the sequencing and structuring of phonological information (Gelfand & Bookheimer, 2003; Moser et al., 2009). This conclusion is compatible with a recent study by Papagno et al. (2017), which compared the effects of direct electrical stimulation of SMG and Broca's area on digit span performance in awake patients undergoing surgery. SMG primarily affected order errors rather than item errors (unlike Broca's area which primarily impacted the number of items recalled). On this basis they proposed that SMG plays a crucial role in memory for serial order. We did not find an increase in item order errors with SMG stimulation but when the phonological form of items are well-learned or a task uses a restricted set of items (like the number words 1-9), the task demands focus on the retention of whole items in order (Quinlan, Roodenrys, & Miller, 2017; Roodenrys & Quinlan, 2000; Saint-Aubin & Poirier, 2000). In contrast, for unfamiliar items (like nonwords), ordering mechanisms are necessary to maintain constituent phonemes in sequence, and consequently,

disruption of ordering mechanisms gives rise to item errors of the form we observed (Jefferies, Frankish, et al., 2006a, 2006b; Jefferies, Jones, et al., 2004; Jefferies, Lambon Ralph, & Baddeley, 2004; Page, Madge, Cumming, & Norris, 2007; Savill, Ashton, et al., 2015).

Our SMG results are also broadly consistent with neuropsychological studies of patients with SMG lesions who show similar effects in immediate serial recall and repetition tasks -- i.e., more difficulty with nonwords than words (Baldo et al., 2012; Jefferies, Crisp, et al., 2006; Verhaegen et al., 2013). In line with the view that SMG supports the capacity to maintain a phonological sequence, lesions to SMG disrupt phonological judgement tasks but *not* verbal tasks that involve well-learned lexical forms in the absence of a sequencing requirement, such as paired associate learning. In other words, the classical distinction between impaired STM and preserved LTM difference might come about because measures of STM rely more on phonological sequencing than LTM tasks (Belleville, Caza, & Peretz, 2003). A limitation of this study is that we did not assess the effect of TMS on language tasks beyond immediate serial recall. The window for recording behavioural data post-TMS was relatively short and we prioritised obtaining adequate numbers of lists in the verbal STM task. However, we selected this site on the basis on previous brain stimulation studies that modulated phonological decision tasks and nonword reading (Hartwigsen et al., 2016; Pattamadilok et al., 2010; Re, Reddy, Roux, & Durand, 2012; Sliwinska et al., 2015, 2012; Stoeckel et al., 2009), as well as long-term phonological learning and retrieval (Meinzer et al., 2013; Perceval, Martin, Copland, Laine, & Meinzer, 2017; Savill, Ashton, et al., 2015).

Our data also do not preclude the possibility that SMG might support an even more basic facet of cognition – such as attention through time – which is critical to phonological processing. Our pattern span control task involved STM but not attention through time. Therefore, future studies could assess the effects of TMS for non-language tasks that involve temporal attention and sequencing requirements. In line with this proposal, recent studies have found effects of SMG stimulation on short-term memory for tone pitch sequences (Schaal et al., 2015) – i.e. sequencing and maintenance beyond language, and speech-motor adaptation performance (Shum, Shiller, Baum, & Gracco, 2011) – in line with a broader auditory-to-motor function.

Finally, it is important to note that the effects of TMS are relatively focal, and SMG is thought to include regions with different functional profiles (Oberhuber et al., 2016). Offline TMS of the form used in this study is not suited to a mapping approach but our findings might not extend to other nearby sites.

Role of anterior temporal cortex

One of our study's novel findings was that it was possible to selectively disrupt word recall with stimulation of left anterior temporal cortex. This site is implicated in heteromodal semantic processing and while this region also contains functional subdivisions (Jackson, Hoffman, Pobric, & Lambon Ralph, 2015; Lambon Ralph et al., 2016; Murphy et al., 2017), the anterior middle temporal gyrus site we stimulated is heteromodal (Margulies et al., 2016; Visser & Lambon Ralph, 2011) and associated with conceptual representation (Murphy et al., 2017). In sharp contrast to the findings for SMG, nonwords were impervious to ATL stimulation. This pattern is broadly consistent with studies of semantic dementia: these patients show preserved verbal STM for nonwords reflecting their intact phonological skills (Jefferies et al., 2005; Majerus et al., 2007), yet disruption of word recall and phonological errors for semantically-degraded items. While phonological migration responses increased for nonwords following SMG stimulation, compatible with its role in phonological ordering, these errors did not notably increase after ATL stimulation. We might have expected to observe an increase in the case of words, in accordance with hypotheses that suggest semantic information can help to maintain phonological sequences (Hoffman, Jefferies, Ehsan, Jones, et al., 2009; Patterson et al., 1994; Savill et al., in press; Savill, Metcalfe, et al., 2015). However, pre-production editing could be used to avoid nonword responses for word lists in healthy people -- leading to omissions rather than phoneme recombination errors. Indeed, a review of the errors indicates that TMS to both stimulation sites resulted in increased omission errors in the recall of words.

Importantly, the temporary semantic disruption of healthy word recall we observed is compatible with (i) accounts of the disruption of word recall in semantic dementia operating at a semantic level, and not just at the level of lexical familiarity (i.e., due to degraded word usage, Papagno et al., 2013) and (ii) accounts of STM that hold that semantic activation necessarily contributes to STM performance (c.f., Kowialiewski & Majerus,

2018), reflecting the neural architecture of the underlying language system responsible for processing single words.

Given that this is the first study looking at ISR in ATL, with a relatively small sample size, and the effects on word recall were small, the results should be regarded as preliminary and in need of replication. This is especially the case because there is increasing evidence that TMS can elicit quite variable effects across people. We have used statistical models that can estimate parameters for stimulation, having controlled for effects of participant and specific items in ISR. We are now actively investigating individual differences in the effects of TMS and how these might relate to differences in underlying brain organisation.

Future directions

Multiple theoretical accounts and neuropsychological evidence might predict that SMG and ATL dissociate with respect to STM function and this study provides evidence that these sites dissociate using a spatially-specific and causal method within the same participants. However, with our offline method we cannot determine whether the disruption(s) to recall performance arose through functional disruption affecting stages of phonological encoding, rehearsal, and/or production at recall—or indeed whether the relative timing of TMS effects differed between the phonological and semantic stimulation sites. Thus, future studies applying online TMS methods to test disruptive effects at different points in time, e.g., encoding/retention vs. retrieval, would help to determine which mechanistic accounts provide the best explanation of the way in which long-term lexical-semantic activation is expressed in STM.

Future studies might also consider additional sites: The choice to stimulate two left-lateralised sites to compare semantic and phonological disruption was guided by scientific, practical and ethical considerations; however, the extent of behavioural disruption (certainly the size of the present ATL effect) may have been mitigated by this design. Given the bilateral representation of semantic memory and bilateral atrophy seen in semantic dementia, future TMS studies that could safely (and comfortably) harness bilateral ATL stimulation might offer a more robust index of the strength of semantic effects.

Concluding comments

This special issue considers whether it is useful to assume the existence of short-term memory buffers specific to one input or output domain. Our findings link different sites to different aspects of verbal STM. In this way, they add to neuropsychological evidence that there are brain regions that support specific processes that contribute to verbal STM, and they suggest that TMS can provide useful converging evidence for the necessary role of a brain region in a specific processing capacity.

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Figure 1

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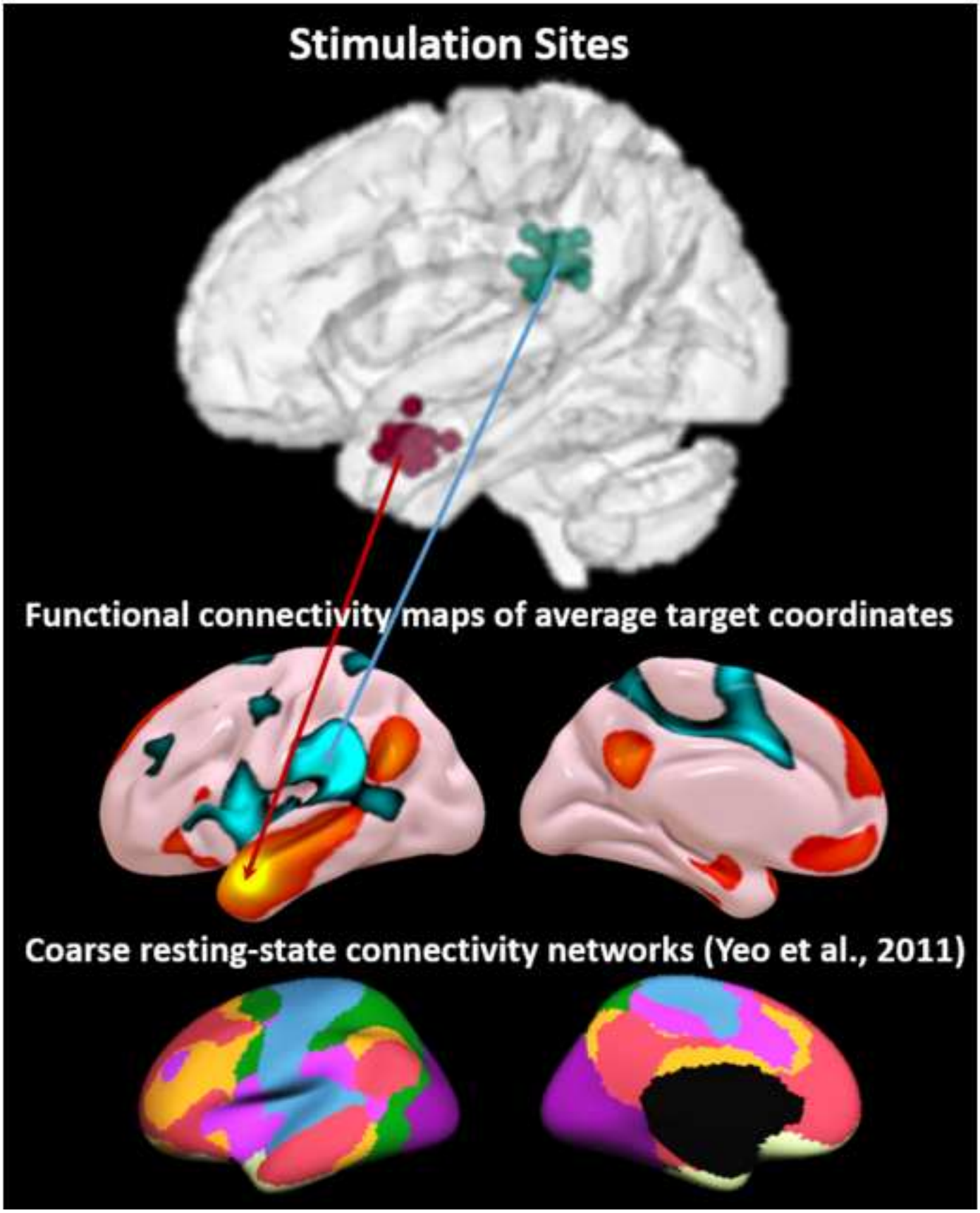

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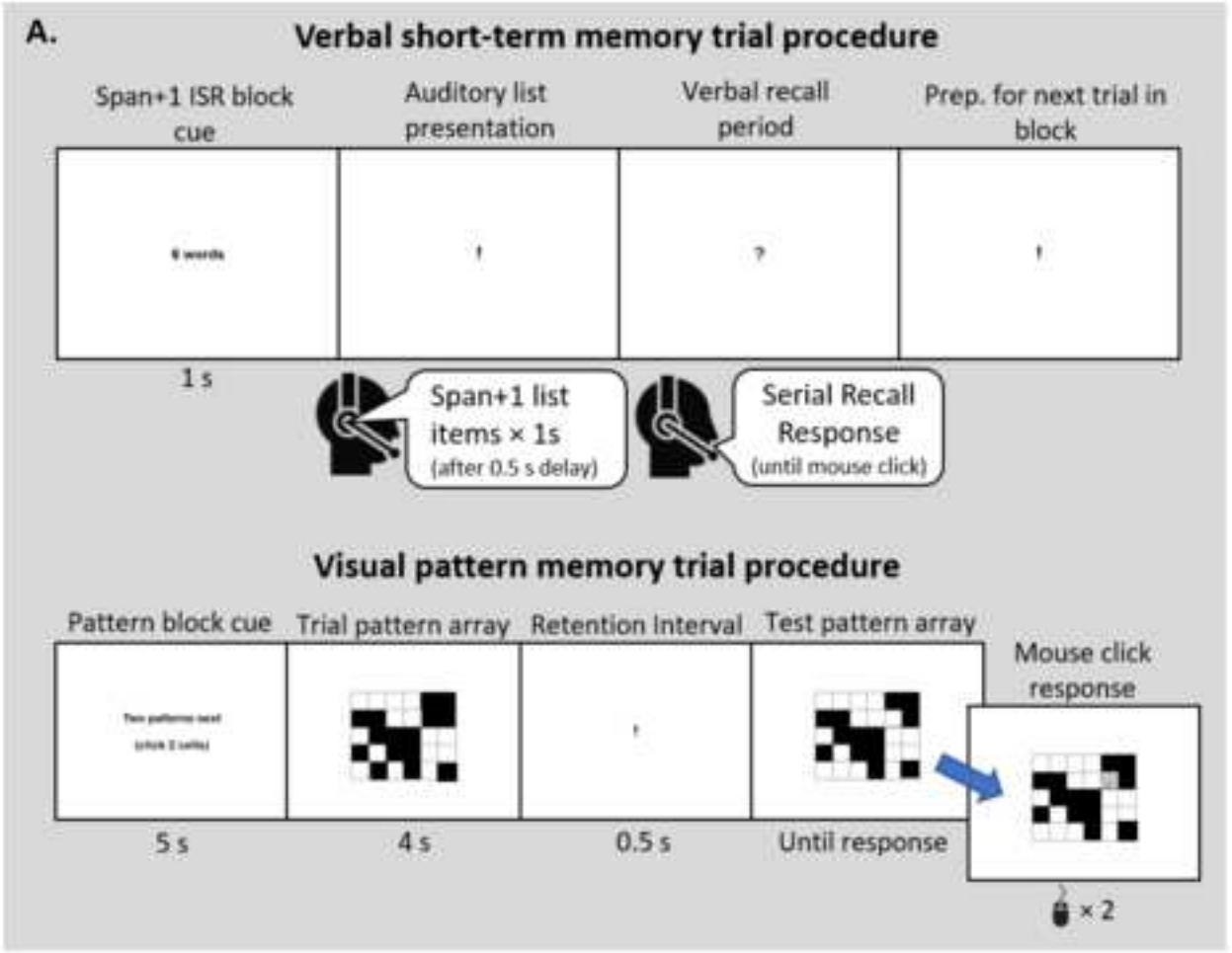

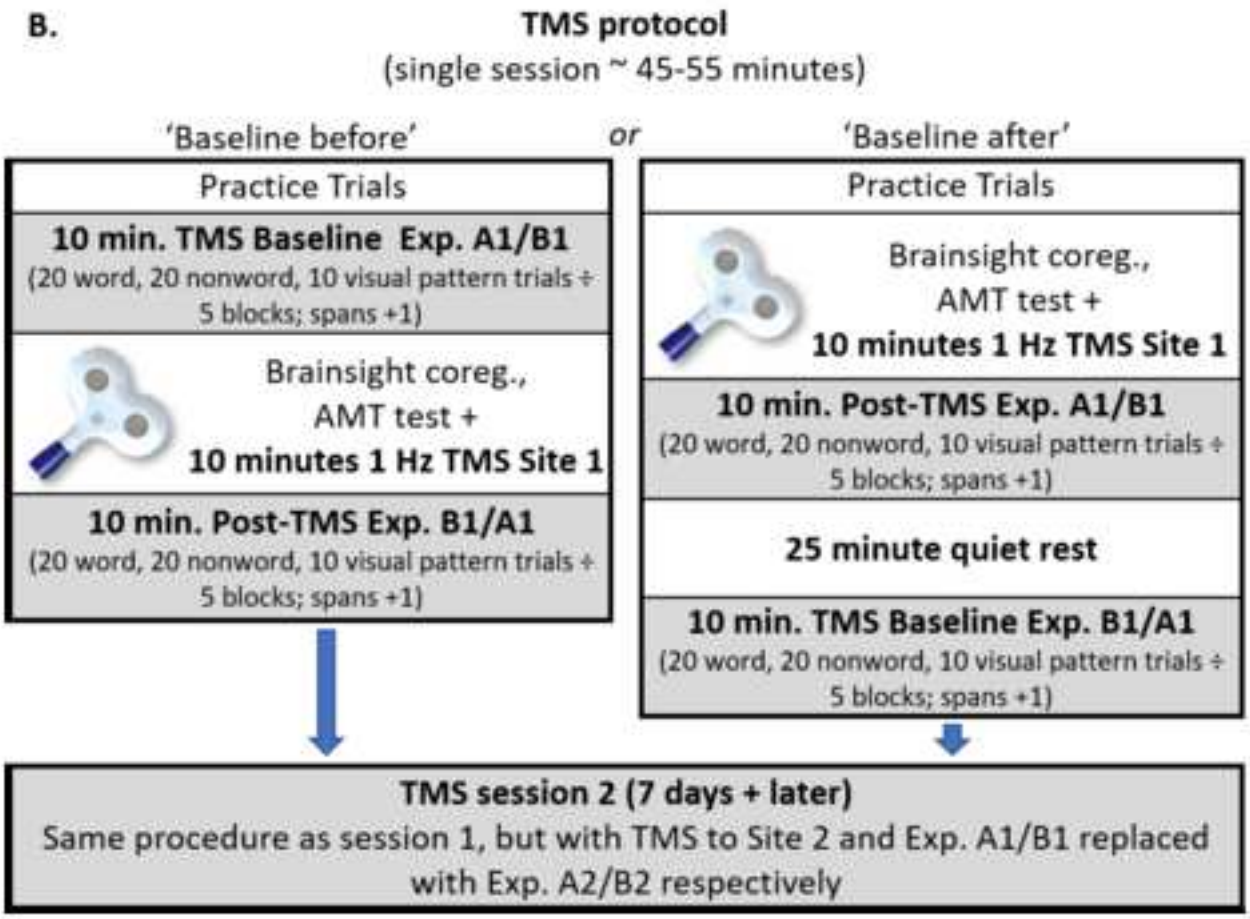

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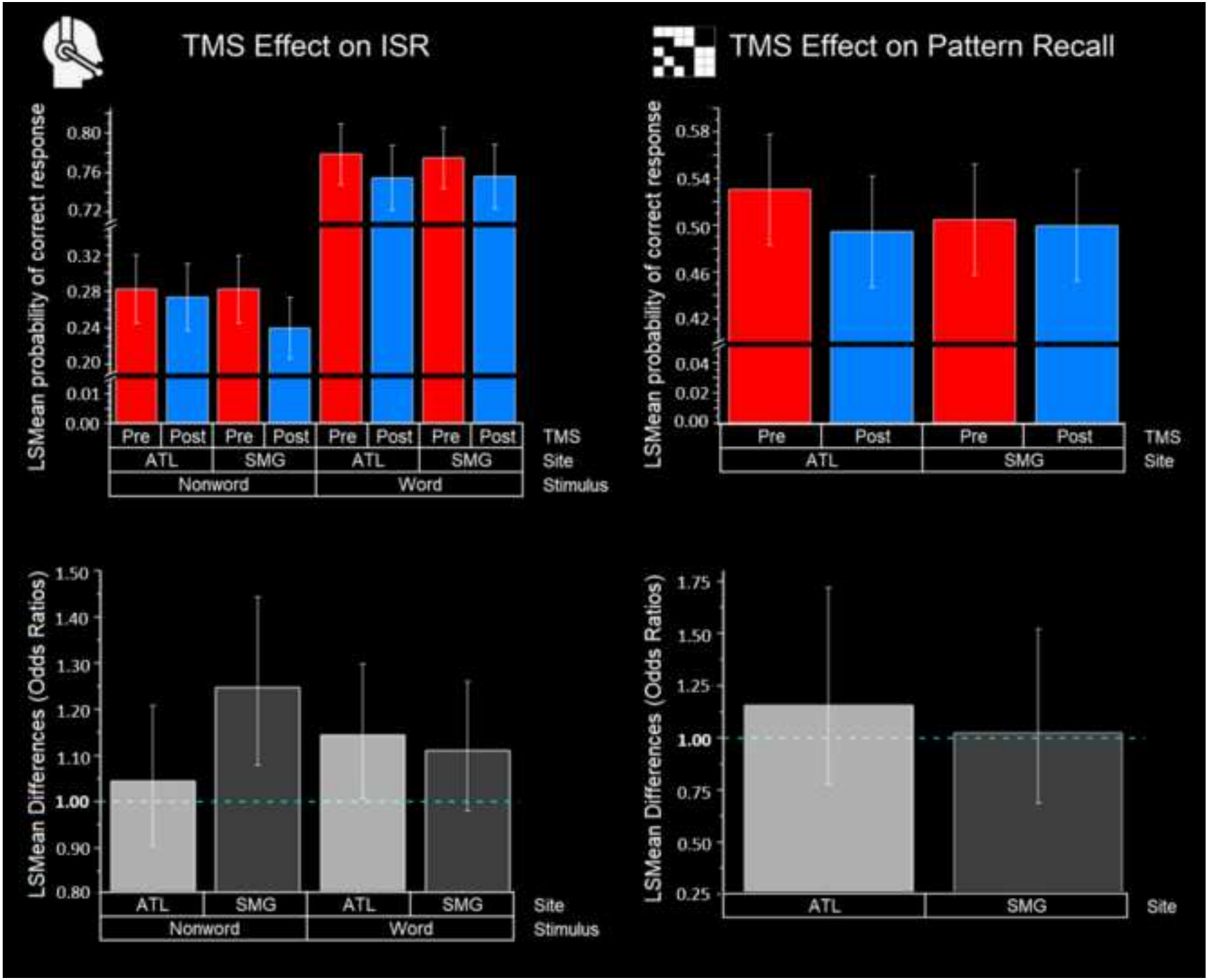
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