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Transcranial magnetic stimulation of the left angular gyrus during encoding does not impair associative memory performance

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Abstract

The left angular gyrus (AG) is thought to play a critical role in episodic retrieval and has been implicated in the recollection of specific details of prior episodes. Motivated by recent fMRI studies in which it was reported that elevated neural activity in left AG during study is predictive of subsequent associative memory, the present study investigated whether the region plays a causal role in associative memory encoding. Participants underwent online transcranial magnetic stimulation (TMS) while encoding word pairs prior to an associative memory test. We predicted that TMS to left AG during encoding would result in reduced subsequent memory accuracy, especially for estimates of recollection. The results did not support this prediction: estimates of both recollection and familiarity-driven recognition were essentially identical for words pairs encoded during TMS to left AG relative to a vertex control site. These results suggest that the left AG may not play a necessary role in associative memory encoding. TMS to left AG did however affect confidence for incorrect ‘intact’ judgments to rearranged pairs and incorrect ‘rearranged’ judgments to intact pairs. These findings suggest that the left AG supports encoding processes that contribute to aspects of subjective mnemonic experience.

Keywords

Parietal Cortex; Recollection; Familiarity; Episodic Memory; Recognition Memory; Neuromodulation

Introduction

Dual-process theory proposes that two qualitatively distinct processes, namely recollection and familiarity, support recognition memory (Yonelinas, 2002). Recollection is associated with retrieval of specific details from a prior encounter whereas familiarity is associated with assessment of an item’s memory strength in the absence of recollection. Consistent with the

above hypothesis, recollection and familiarity have distinct neural correlates (Aggleton & Brown, 2006; Eichenbaum, Yonelinas, & Ranganath, 2007; Rugg & Vilberg, 2013; Vilberg & Rugg, 2008; Yonelinas, Aly, Wang, & Koen, 2010). Of relevance to the present experiment, there is a large body of evidence linking neural activity in the lateral parietal cortex, and particularly the left angular gyrus (AG), to recollection (Berryhill, 2012; Ramanan, Piguet, & Irish, 2017; Rugg & King, 2017; Vilberg & Rugg, 2008). Notably, functional imaging studies have consistently reported elevated neural activity in the left AG during retrieval associated with successful recollection relative to familiarity-based recognition (for recent empirical evidence, see Hutchinson et al., 2014; King, de Chastelaine, Elward, Wang, & Rugg, 2015; Richter, Cooper, Bays, & Simons, 2016; for review, see Rugg & King, 2017). Moreover, patients with damage to the left parietal cortex encompassing the left AG have been reported to show impairments on subjective measures of recollection (Ally, Simons, McKeever, Peers, & Budson, 2008; Davidson et al., 2008; Ciaramelli et al., 2017; Levy, 2012; Simons, Peers, Mazuz, Berryhill, & Olson, 2010; Stamenova et al., 2017), to recall fewer autobiographical details (Berryhill, Phuong, Picasso, Cabeza, & Olson, 2007; Berryhill, Picasso, Arnold, Drowos, & Olson, 2010), and to demonstrate severely impaired cued-recall of paired associates (Ben-Zvi, Soroker, & Levy, 2015; but see Stamenova et al., 2017; for related null effects of parietal lesions on associative recognition, see Berryhill, Drowos, & Olson, 2009). The link between the left AG and episodic recollection is further supported by studies reporting that transcranial magnetic stimulation (TMS) to the left AG during test impairs retrieval of episodic details (Thakral, Madore, & Schacter, 2017), reduces the confidence of recollection-based memory judgments (Yazar, Bergstrom, & Simons, 2014), and impairs retrieval of multimodal episodic information (Yazar, Bergstrom, & Simons, 2017).

Whereas the above neuroimaging and TMS evidence (and, more ambiguously, the lesion evidence; see below) implicates the left AG in memory retrieval, the role of this region in memory encoding is less clear. The aim of the present experiment is to investigate possible links between the left AG and associative memory encoding by using TMS to transiently disrupt its functional integrity. The rationale for the experiment stems from recent neuroimaging studies in which it was reported that increased activity in the left AG during a relational semantic encoding task is predictive of subsequent recollection (de Chastelaine, Mattson, Wang, Donley, & Rugg, 2016; de Chastelaine, Wang, Minton, Muftuler, & Rugg, 2011; Wong, de Chastelaine, & Rugg, 2013). In each of these three studies, the left AG showed increased neural activity during encoding of subsequently recollected word pairs relative to pairs where the association was later forgotten. Thus, these findings establish a relationship between neural activity in the left AG and encoding processes that support subsequent recollection of associative information, processes that may be tied to the region's proposed role in semantic integration (Price, Peelle, Bonner, Grossman, & Hamilton, 2016).

While suggestive, these neuroimaging findings do not establish a causal link between the left AG and associative encoding due to the correlational nature of the data. Although lesion-deficit studies can establish a necessary role for a brain region in memory performance, these studies are severely limited in their ability to ascribe the role of a brain region to encoding, retrieval or both (Rorden & Karnath, 2004; but, see Ben-Zvi et al., 2015, for a procedure intended to address this issue). Moreover, naturally-occurring lesions do not

necessarily respect architectonic boundaries and can encompass multiple brain regions, further limiting the ability to establish a strong link between a specific region and a given cognitive function. And, whereas TMS to left AG at the time of retrieval has been reported to influence recollection (see above), these findings do not preclude a role for the left AG in memory encoding. Of relevance to this issue, Jones, Gozenman, and Berryhill (2014) reported that transcranial direct current stimulation (tDCS) of the left parietal cortex during encoding improved subsequent memory performance. However, given the limited spatial resolution of tDCS (Woods et al., 2016; Priori, Hallett, & Rothwell, 2009), it is unclear whether the reported effects arose from modulation of the left AG or modulation of adjacent cortical regions. Beyond this limited evidence, to our knowledge, no studies have been reported in which neurostimulation was delivered to the left AG during episodic encoding.

TMS is well suited to overcome the various limitations discussed above because it can be used to modulate neural function during specific mnemonic phases (in the present case, encoding) and can target a relatively circumscribed cortical region (Priori et al., 2009; Rossini et al., 2015). The present study adapted the associative recognition paradigm employed by de Chastelaine and colleagues (2011; 2016), in which robust left AG effects predictive of the subsequent recollection of word pairs were reported. In the present study, we administered TMS to the left AG or a control site (the vertex) while participants incidentally encoded word pairs prior to a subsequent associative recognition test (see Figure 1A). This paradigm allows for the separate estimation of the influences of recollection and familiarity (cf. de Chastelaine, Mattson, Wang, Donley, & Rugg, 2017), which is critical in light of the link discussed above between recollection (but not familiarity) and the left AG (Vilberg & Rugg, 2008). Given the evidence that brain damage encompassing left AG (e.g., Ciaramelli et al., 2017; Davidson et al., 2008; Stamenova et al., 2017) and application of TMS to the region (Yazar et al., 2014) result in impaired subjective experiences of recollection, we required participants to provide a confidence judgment on each test trial. If the left AG has a causal role in the encoding of associative information, we would expect later associative recognition performance to be worse for pairs encoded during TMS to left AG than during TMS to a control site. Moreover, we expected TMS to left AG to have greater effect on estimates of recollection rather than of familiarity.

Methods

Ethics Statement

This experiment was approved by the Institutional Review Board of the University of Texas at Dallas, and all participants provided written informed consent prior to participation. The TMS protocols for this study were within standard safety limits (Rossi, Hallett, Rossini, Pascual-Leone, & The Safety of TMS Consensus Group, 2009; Rossini et al., 2015).

Participants

Twenty-one healthy young adults volunteered and were monetarily compensated for their time (\$30/hour). All participants were right-handed, native English speakers with normal or corrected-to-normal vision, and had a structural MRI scan available because of participation in a prior fMRI study. Participants self-reporting contraindications for TMS were excluded.

The exclusion criteria were: potential pregnancy, prior or current neurological illness, current use of psychoactive medications, prior head injury or concussion, frequent or severe headaches/migraines, or a personal or family history of seizure or epilepsy. Additionally, prior to undergoing TMS, all participants acknowledged that they had not consumed alcohol in the previous 24 hours.

Data from one participant were excluded from the analysis due to experimenter error. Additionally, due to a technical error, data from one of the two angular gyrus study sessions was lost for one other participant. The data from the remaining 20 participants (9 females, mean age: 22.5 years; range: 18–27 years) contributed to the results presented below. This sample size is slightly larger than prior TMS studies examining memory encoding (e.g., Innocenti et al., 2010; Sandrini, Cappa, Rossi, Rossini, & Miniussi, 2003; Rossi et al., 2001; Rossi et al., 2006).

MRI Acquisition and Processing

MRI data were acquired with a 3T Philips Achieva MRI scanner (Philips Medical Systems, Andover, MA, USA) equipped with a 32-channel receiver head coil. T1-weighted structural images (MPRAGE sequence, 240×240 matrix, 1 mm isotropic voxels) were acquired. Each T1 image was normalized to MNI space using Statistical Parametric Mapping (SPM8) software. The transformation matrix was then used to back-project an angular gyrus ROI into each participants' native space using neuronavigation software (see TMS Procedure).

Associative Memory Task

Stimuli and Apparatus—Cogent 2000 software (www.vislab.ucl.ac.uk/cogent_2000.php) implemented in Matlab 2011b (www.mathworks.com) was used for stimulus presentation. The stimuli were presented on a 30" Dell LCD monitor with a screen resolution of 1024 X 768 pixels at a viewing distance of ~100 cm. The stimuli comprised 256 semantically unrelated word pairs (de Chastelaine et al., 2011). For each participant, four sets of 48 randomly selected pairs of concrete words served as the stimuli for the study phase and the remaining 64 word pairs served as new items for the test phase. Two sets of 48 word pairs were assigned to the angular gyrus stimulation condition, and the remaining two sets were assigned to the vertex (control) stimulation condition. A single test list was created that comprised 128 *intact* word pairs (32 from each of the four study lists), 64 *rearranged* word pairs (16 from each of the four study lists), and 64 *new* word pairs. Rearranged word pairs were created by re-pairing word pairs presented within the same study phase. A randomized stimulus set was created for each participant.

An additional 16 word pairs with similar characteristics to those just described were used as practice stimuli. The practice study list comprised 12 pairs, and the practice test list comprised 8 intact word pairs from the practice study list, 4 rearranged word pairs, and 4 new word pairs.

Study Phase—Participants completed the practice study phase prior to the study phase proper. The study phase proper was completed while undergoing TMS and was split into four sessions. Two sessions were assigned to the angular gyrus stimulation condition and the

remaining two sessions were assigned to the vertex stimulation condition. The order of targeted stimulation site was determined using an ABAB design, which was counterbalanced across participants. There was a short break (approximately 1–3 minutes) between each study session to allow the experimenters to align the TMS coil to the new TMS target. The study instructions did not reference the subsequent test phase, and thus the study phase was completed under incidental encoding instructions. Following each study block, participants reported their level of discomfort from the TMS procedure on a 10-point scale (1-no discomfort, 10-high discomfort).

Word pairs in each study block were presented in 30-point Helvetica font with one member of the pair presented above, and one below, a centrally located fixation cross. For each study pair, participants were required to indicate which of the two objects denoted by the word was more likely to ‘fit’ into the other (cf. de Chastelaine et al., 2011). Responses were entered with the right hand using the ‘1’ and ‘2’ keys on a number pad. Pairs were presented on the monitor for 1500 ms and followed by a white fixation cross for 1250 ms. Participants were instructed to enter responses as quickly as possible before the onset of the next word pair.

Test Phase—Following the final study phase, participants completed the practice test phase and then the test phase proper. TMS was not administered during the test phase. Participants were shown word pairs one at a time and required to make a memory judgment using one of three responses. An ‘intact’ response was required if participants recognized both words and were able to recollect that the two words were presented as a pair during the study phase. Participants were instructed to respond ‘rearranged’ if they recognized both words but were unable to remember if the two words had been presented together previously. A ‘rearranged’ response could also be entered if participants were able to recollect that at least one word in the pair was presented with a different word during the study phase. Lastly, a ‘new’ response was required when participants did not recognize either word in the pair or were only able to recognize one of the words in the pair. Responses were self-paced, and participants pressed the ‘1’, ‘2’, and ‘3’ keys on the number pad with their right hand to make an ‘Intact’, ‘Rearranged’, and ‘New’ response, respectively.

After each memory judgment had been entered, participants were asked to rate how confident they were in their decision. The three possible responses were ‘High’, ‘Low’, and ‘Guess’. This confidence judgment was also self-paced, and participants used the ‘1’, ‘2’, and ‘3’ keys on the number pad with their right hand, respectively.

TMS Procedure

Equipment and co-registration—TMS was delivered using a Magstim Super Rapid2 stimulator equipped with a 70-mm figure-of-eight coil. Frameless stereotaxy was used to co-register participants to their MRI scan and to align the coil over the target stimulation sites usingBrainsight (Rogue Research; www.rogue-research.com/) software equipped with a Polaris infrared camera. During co-registration and TMS, each participant’s head was stabilized with a chin- and head-rest to minimize movement.

Four anatomical landmarks were identified on the skin reconstruction of a participant’s MRI scan: nasion, nose tip, and bilateral pre-auricular points. The nose tip was excluded if it was

outside the field-of-view of the structural MRI, leaving only three points for co-registration. The outer canthi of the left and right eyes were used in place of the pre-auricular points if the latter were not identifiable on the skin reconstruction. Co-registration was performed by identifying the relevant anatomical landmarks on the participant's head using a pointer. Co-registration allowed us to track the location of the coil in real-time relative to the ROIs targeted for stimulation for each participant. Reflective markers attached to the TMS coil and each participant's head (via an elastic velcro strap) were used to monitor coil position and head location, respectively, using the infrared camera.

Stimulation Protocol—TMS was delivered during the study phases either to the left AG or the vertex. The left AG coordinate (MNI coordinates, $x = -44$, $y = -64$, $z = 27$) was determined from an associative memory encoding study in our lab that reported data from a sample of 36 young adults aged 18–30 years (de Chastelaine et al., 2016). The coordinate was identified as the center-of-mass of a left AG cluster that demonstrated a robust 'positive' subsequent memory effect (associative hits > associative misses; see Fig. 1). The coordinate was very close to both the peak coordinate ($x = -39$, $y = -64$, $z = 22$) and a sub-peak ($x = -42$, $y = -67$, $z = 25$) of the same cluster. The vertex was selected for the control stimulation condition (Sandrini et al., 2003; Thakral et al., 2017; Yazar et al., 2014, 2017), and was identified for each participant as the skull location overlying where the central sulcus and longitudinal fissure intersected.

The TMS protocol administered during the encoding task to each ROI was similar to online stimulation protocols used in prior research reporting reduced memory performance following stimulation to dorsolateral prefrontal cortex (Innocenti et al., 2010). The TMS pulse train onset 500 ms after the word pair first appeared on the display monitor, and comprised a train of 5 pulses delivered at 10 Hz. The onset latency of the first TMS pulse was selected to be in line with the ERP literature showing that subsequent memory effects onset approximately 300–600 ms after stimulus presentation (Rugg, 1995; Wilding & Ranganath, 2012). Stimulator intensity was determined separately for each participant and set at 90% of the resting motor threshold. Coil positioning and orientation relative to the TMS target was continually monitored during each study phase. If the placement deviated more the 3mm from the initial target location, the study phase and TMS stimulation were paused and the coil realigned.

Motor Threshold—The TMS intensity applied during the study phase was determined from the motor threshold. For each participant, a threshold was determined using single pulse TMS over the left motor cortex (visually identified on the structural MRI), and was defined as the lowest stimulator intensity that produced 5 out of 10 motor responses in the right hand. The initial intensity was set at 70% of maximum stimulator output, and was reduced in 5% increments until a motor response could not be visually detected for 5 of 10 consecutive pulses. The intensity was then increased in 3% intervals until 5 of 10 motor responses were observed. Finally, stimulator intensity was decreased in 1% intervals until 5 of 10 pulses were not observed. Motor threshold was set at the final stimulator output that produced 5 out of 10 visible muscle contractions.

The mean motor threshold was 59% (SD = 8%) of maximum stimulator output and ranged between 45% and 70%. Stimulator intensity never exceeded 70% of maximum output. Thus, motor threshold was set at 70% if no motor response was evident at this intensity.

Data Analysis

Statistical analyses were carried out using JASP software (JASP Team, 2017). Results from paired-samples t-tests (two-tailed) and repeated measures ANOVA were considered significant at $p < .05$. Effect size estimates (Cohen's d or partial- η^2) are reported for all effects (Cohen, 1988).

In addition to the null hypothesis statistics, we report results from Bayesian t-tests (Rouder, Speckman, Sun, Morey, & Iverson, 2009) and repeated measures ANOVA (Rouder, Morey, Verhagen, Swagman, & Wagenmakers, 2017) using JASP (Wagenmakers et al., 2018). Specifically, we calculate and report Bayes Factors (BF) corresponding to evidence in favor of the effect of interest (e.g., TMS target) relative to the null model (i.e., the prior). We report these values as BF_{10} , with values > 1 indicating increased evidence favoring the alternative hypothesis. For instance, a BF_{10} value of 5 indicates that the alternative model is 5 times more likely than is the null model, whereas a BF_{10} value of .2 indicates that the null model is 5 times more likely than the alternative model. The BF_{10} for ANOVA main effects and interactions were computed using the 'BF Inclusion' (reported here as BF_{10} for consistency) values output by JASP with the 'Across Matched Models' option. This approach computes BF by comparing all models with an effect of interest (e.g., TMS target) to equivalent models without the effect of interest (cf. Mathot, 2017). Bayes factors are interpreted using the categorical labels proposed by Jeffreys (1961), such that BF_{10} values between 1–3 correspond to anecdotal evidence, between 3–10 correspond to substantial evidence, and 10–30 correspond to strong evidence for the effect of interest. We primarily focus the interpretation of the BF_{10} values for effects involving the factor of TMS target (i.e. AG vs. vertex).

Dependent Measures—The analyses reported below focused on subjective discomfort ratings from TMS, reaction times (RTs) to study and test judgments, average confidence ratings for correct test judgments to intact and rearranged pairs, and estimates of recollection and familiarity. Trials that did not receive a response during the study phase were excluded from analysis.

Discomfort ratings were defined as the highest reported level of discomfort for a given TMS target across both stimulation sessions. Median RTs for study and test responses were computed separately for intact trials judged 'intact' (associative hits) and 'rearranged' (associative misses) for each TMS target condition. Study and test RTs were analysed separately. Test RTs were computed only for the initial 'intact', 'rearranged', and 'new' responses. Prior to computing the median RT for each participant, trials with RTs < 400 ms or greater than 3 absolute standard deviations from the mean of all intact trials were excluded.

Analysis of the confidence responses during the test phase focused on average confidence ratings for correct and incorrect responses to intact and rearranged word pairs. Confidence

ratings at test phase were coded with values of 3, 2, and 1 for high, middle, and low responses, respectively.

Associative memory performance was assessed using estimates of recollection and familiarity for each TMS target using previously described formulas (de Chastelaine et al., 2017). Recollection estimates, hereafter referred to as pR , were computed with the following formula:

$$pR = p(\text{Intact}|\text{'Intact'}) - p(\text{Rearranged}|\text{'Intact'})$$

Familiarity, hereafter referred to as pF , was computed under the independence assumption (cf. Jacoby, 1991; Yonelinas & Jacoby, 1995) with the following formula:

$$pF = \frac{p(\text{Intact}|\text{'Rearranged'})}{1 - p(\text{Intact}|\text{'Intact'})} - \frac{p(\text{New}|\text{'Rearranged'})}{1 - p(\text{New}|\text{'Intact'})}$$

Note that the second term in this equation involving new trials is identical for the two TMS targets, and thus the important term in the pF equation is the corrected proportion of 'rearranged' responses to intact trials. For consistency, pF for the two TMS targets is reported as computed by the above equation.

Results

Discomfort Ratings

The average reported discomfort ratings for TMS to left AG ($M = 3.00$; $SE = .37$; range: 1–7) were significantly higher than ratings for TMS to vertex ($M = 1.70$; $SE = .16$; range: 1–3), $t(19) = 3.90$, $SE_{\text{Diff}} = .33$, $p < .001$, Cohen's $d = .87$, $BF_{10} = 37.87$. According to the BF_{10} value, the data provide strong evidence for the effect of left AG TMS on reported discomfort.

Study Reaction Times

The median RTs for study judgments are reported in the top half of Table 1. A 2 (TMS target: left AG vs. Vertex) X 2 (Subsequent Memory: Associative Hit vs. Miss) repeated measures ANOVA revealed no significant effects of TMS target, $F(1,19) = .79$, $MSe = 21,449$, $p = .38$, $\text{partial-}\eta^2 = .04$, $BF_{10} = .46$, Subsequent Memory, $F(1,19) = 3.73$, $MSe = 4,002$, $p = .07$, $\text{partial-}\eta^2 = .16$, $BF_{10} = .43$, nor the interaction term, $F(1,19) = .56$, $MSe = 5,506$, $p = .46$, $\text{partial-}\eta^2 = .03$, $BF_{10} = .37$. The data provide substantial evidence for the null main effect of TMS target, and somewhat weaker ('anecdotal') evidence for the null hypothesis for the interaction.

Test Reaction Times

The median test RTs for intact trials are shown in the bottom half of Table 2. A 2 (TMS target: left AG vs. Vertex) X 2 (Memory: Associative Hit vs. Miss) repeated measures ANOVA found no significant main effect of TMS target, $F(1,19) = 3.56$, $MSe = 85,005$, $p = .07$, $\text{partial-}\eta^2 = .16$, $BF_{10} = .44$, with the BF_{10} value indicating substantial evidence for the

null hypothesis. The main effect of Memory, $F(1,19) = 75.17$, $MSe = 355.957$, $p < .001$, partial- $\eta^2 = .80$, $BF_{10} > 4.92e^{13}$, and the TMS target by Memory interaction, $F(1,19) = 4.89$, $MSe = 124.975$, $p = .04$, partial- $\eta^2 = .21$, $BF_{10} = 1.07$, were both significant. As can be seen in Table 2, the interaction appears to be driven by slower RTs for associative miss trials following TMS to left AG than to vertex, $t(19) = 2.36$, $SE_{Diff} = 126.06$, $p = .03$, Cohen's $d = .53$, $BF_{10} = 2.14$, whereas there was no reliable difference in test RTs for associative hits between the two TMS targets, $t(19) = .72$, $SE_{Diff} = 71.47$, $p = .48$, Cohen's $d = .16$, $BF_{10} = .29$. It should be noted that the interaction term was associated with a BF_{10} near 1, suggesting that the data provide little or no evidence in favor of either the alternative or the null hypothesis.

Test Confidence

The average confidence ratings to correctly judged intact and rearranged pairs are reported in top panel of Table 2. A 2 (TMS target: left AG vs. Vertex) X 2 (Pair Type: Intact vs. Rearranged) repeated measures ANOVA revealed a significant effect of Pair Type, $F(1,19) = 49.28$, $MSe = .03$, $p < .001$, partial- $\eta^2 = .72$, $BF_{10} > 9.48e^8$, which was driven by higher confidence in correct 'intact' responses relative to correct 'rearranged' responses. However, neither the effect of TMS target, $F(1,19) = 2.02$, $MSe = .01$, $p = .17$, partial- $\eta^2 = .10$, $BF_{10} = .46$, nor the interaction between TMS target and Pair Type, $F(1,19) = .74$, $MSe = .01$, $p = .40$, partial- $\eta^2 = .04$, $BF_{10} = .39$, were significant. According the Bayes factors, the data provide substantial and anecdotal evidence for the null hypothesis, respectively.

The bottom panel of Table 2 reports the average confidence to intact and rearranged pairs given an incorrect 'rearranged' and 'intact' response, respectively. Note that two participants were excluded from this analysis due to their having zero incorrect 'intact' responses to rearranged pairs. Although there was no significant main effect of TMS target, $F(1,17) = 1.18$, $MSe = .05$, $p = .29$, partial- $\eta^2 = .07$, $BF_{10} = .32$, or Pair Type, $F(1,17) = 1.81$, $MSe = .13$, $p = .20$, $BF_{10} = .80$, partial- $\eta^2 = .10$, there was a significant interaction between the two factors, $F(1,17) = 15.20$, $MSe = .04$, $p = .001$, partial- $\eta^2 = .47$, $BF_{10} = 8.04$, with substantial evidence in favor of the alternative hypothesis for the interaction. Relative to vertex stimulation, TMS to left AG *reduced* confidence for incorrect 'rearranged' decisions to intact pairs (i.e., associative misses), $t(17) = 2.44$, $SE_{Diff} = .05$, $p = .03$, Cohen's $d = .58$, $BF_{10} = 2.44$, but *increased* confidence to incorrect 'intact' decisions to rearranged pairs (i.e., associative false alarms), $t(17) = 2.75$, $SE_{Diff} = .09$, $p = .01$, Cohen's $d = .65$, $BF_{10} = 4.07$ (see Table 2). According to the BF_{10} values, the data provide anecdotal and substantial evidence in favour of these two simple effects respectively.

Estimates of Recollection and Familiarity

Table 3 reports the proportion of 'intact', 'rearranged' and 'new' test responses to the different pair types. As is evident from the table, these proportions are very similar following TMS to either the angular gyrus and the vertex. Figure 2 plots the recollection (pR) and familiarity (pF) estimates for the two TMS targets. No significant difference was observed between pR estimates following TMS to left AG ($M = .51$, $SE = .03$) and vertex ($M = .51$; $SE = .04$), $t(19) = .04$, $SE_{Diff} = .03$, $p = .97$, Cohen's $d = .01$, $BF_{10} = .23$. In addition, there was no significant difference in pF estimates following TMS to left AG ($M = .47$, $SE = .04$)

and vertex ($M = .49$, $SE = .05$), $t(19) = .63$, $SE_{\text{Diff}} = .02$, $p = .537$, Cohen's $d = .14$, $BF_{10} = .28$. Both of the above Bayes factors indicate the data provide substantial evidence for the null hypothesis that left AG TMS does not affect recollection or familiarity estimates.

Discussion

The present study employed online TMS to follow up prior fMRI findings that neural activity in the left AG during associative memory encoding is predictive of subsequent recollection of the studied word pairs (de Chastelaine et al., 2016; Wong et al., 2013; de Chastelaine et al., 2011). Thus, to the extent that the left AG plays a necessary role in the encoding processes that support subsequent recollection, we expected TMS to the region to lead to reduced associative recognition. We further predicted that TMS to the left AG would have little or no impact on estimates of familiarity. Our results provide no evidence however that TMS to left AG during encoding reduces subsequent memory performance. Notably, according to the Bayes factor categories proposed by Jeffreys (1961), the present data provide substantial evidence favoring the null hypothesis for effects of left AG TMS on estimates of both recollection and familiarity. As is evident from Figure 2, these estimates were essentially identical for word pairs encoded during TMS to left AG relative to the vertex control site. Although subject to several caveats discussed below, taken at face value these results suggest that prior fMRI findings of left AG subsequent memory effects are not indicative of a necessary role for the region in associative encoding.

The present findings lend support to the proposal of Ben-Zvi and colleagues (2015) that damage to left parietal cortex that includes the left AG impairs cued recall of paired associates through its effects on retrieval rather than encoding. Across three experiments, Ben-Zvi and colleagues reported that patients with lateral parietal lesions acquired novel item-item associations at rates similar to healthy controls, a finding which they took as evidence that the lesions disproportionately affected retrieval processes. However, as clearly stated by Ben-Zvi and colleagues, such evidence in chronically lesioned patients is only suggestive. The present findings converge with their results, and cast further doubt on a necessary role for the left AG in episodic encoding.

Our findings also have potential implications for prior research using tDCS to investigate the relationship between left parietal cortex and memory encoding (Jones et al., 2014), in which it was reported that tDCS during encoding improves subsequent long-term memory performance. As was noted in the Introduction, tDCS has lower spatial specificity than TMS (Priori et al., 2009), making it difficult to identify the precise neural underpinnings of these prior tDCS findings. The present results suggest that stimulation of the left AG during memory encoding is unlikely to account for the effects reported by Jones and colleagues (2014).

Although we found negligible effects of left AG TMS on 'objective' estimates recollection and familiarity derived from the associative recognition procedure, left AG TMS did reliably affect subjective reports of confidence for incorrectly judged test items. Specifically, TMS to left AG resulted in lower confidence for associative misses (Intact pairs given an incorrect 'rearranged' response) and higher confidence in associative false alarms (Rearranged pairs

incorrectly called ‘intact’). That is, TMS to left AG caused participants to shift their confidence ratings towards incorrect ‘intact’ judgments and away from incorrect ‘rearranged’ judgments. Given the unanticipated nature of this pattern of effects, they are clearly in need of replication. It is tempting however to speculate that they are related to prior patient (Davidson et al., 2008; Simons et al., 2010; Ally et al., 2008; Levy, 2012; Ciaramelli et al., 2017; Stamenova et al., 2017) and TMS evidence (Yazar et al., 2014) implicating the left AG in subjective aspects of recollection rather than its objective accuracy.

How might these findings be accounted for? We tentatively speculate that they result from the influence of TMS on encoding processes that support a ‘recall-to-reject’ strategy on the subsequent memory test (i.e., the ability to reject rearranged test pairs as intact by recollecting the studied pair-mate of one or both items; Rotello, Macmillan, & Van Tassel, 2000). By this account, a weaker recall-to-reject signal results in increased confidence for rearranged pairs incorrectly judged ‘intact’ because participants are less able to counteract the familiarity (or fluency) of the test pairs that results from having recently studied each of the items, albeit on separate study trials (cf. Jacoby, 1991). A critical assumption of this account is that TMS to left AG had no detectable effect on study trials where encoding was sufficiently effective to support veridical associative recollection on the subsequent memory test. This assumption is *ad hoc* at present, and could justifiably be criticized as circular. Obviously, this account, as well as others, cannot be evaluated without the benefit of further experimentation.

There are several limitations of the present study that bear mention. First, we targeted the center of mass of the left AG cluster previously reported to show fMRI subsequent associative memory effects under the assumption that this region would likely to be closely linked with successful encoding. However, the AG is a heterogeneous region that comprises at least two, and probably more, architectonically and functionally dissociable sub-regions (Rugg & King, 2017; Caspers et al., 2006), and it is possible that the region we selected for TMS was either off-target, or too circumscribed (an issue that is less problematic for tDCS, when stimulation is spatially more diffuse). In a similar vein, the left AG region targeted here was identified from the average fMRI effect across a group of young adults. Thus, it is possible that our null findings arose because the location of the left AG region critical for encoding differs significantly across individuals (Caspers et al., 2006). Finally, it should be noted that our stimulation protocol was unilateral, leaving open the possibility that the right AG also can support associative memory encoding. This possibility gains credence from the fact that the majority of the studies reporting mnemonic effects of damage to lateral parietal cortex have examined patients with bilateral lesions (Ally et al., 2008; Ciaramelli et al., 2017; Davidson et al., 2008; Levy, 2012; Simons et al., 2010; Stamenova et al., 2017). Indeed, Ben-Zvi and colleagues (2015) reported that impaired cued recall of picture-picture and picture-sound associates was evident only after bilateral rather than unilateral lesions. It is also noteworthy, however that recall of word-word associations (as were employed in the present study) was reported by these authors to be impaired in patients with lesions restricted to left lateral parietal cortex and was related specifically to the involvement of the AG.

In conclusion, we found that TMS to the left AG, a region linked with successful memory associative memory encoding according to fMRI (de Chastelaine et al., 2016; de Chastelaine et al., 2011; Wong et al., 2013), had no detectable effect on subsequent associative memory performance when stimulation was administered during a study phase. There was, however, evidence for an effect of left AG on confidence judgments made during the subsequent memory test. Clearly, additional research is needed to determine the exact role or roles of the left AG in episodic memory encoding.

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Figure 1.

(A) Example of experimental stimuli, timing, and the online inhibitory transcranial magnetic stimulation (TMS) protocol (i.e., a train of 5 TMS pulses delivered at 10 Hz, starting 500 ms after stimulus onset). (B) Depiction of the left angular gyrus ROI overlaid on a young adult anatomical template created from the anatomical images reported in de Chastelaine et al. (2016). The cluster was defined from a subsequent memory effect analysis that contrasted associative hits (i.e., intact trials subsequently assigned an 'intact' response) greater than associative miss (i.e., intact trials subsequently assigned an 'rearranged' response) thresholded at $p < .001$ (uncorrected) with a 21 minimum voxel extent. The red dot indicates the center of mass.

Figure 2.

Plot of the recollection (pR; left) and familiarity (pF; right) estimates for the left angular gyrus and vertex TMS targets. The number of participants showing a decrease in pR and pF following TMS to left angular gyrus were 9/20 and 11/20, respectively.

Table 1.

Mean (with standard errors) of the median reaction times (RTs, in ms) the study (top panel) and test (bottom panel) judgments as a function of TMS target and memory.

Subsequent Memory	Left Angular Gyrus	Vertex
Study RT		
Associative Hit	1393 (76)	1409 (70)
Associative Miss	1406 (75)	1451 (73)
Test RT		
Associative Hit	2105 (139)	2157 (163)
Associative Miss	1406 (253)	3139 (202)

Note. Associative hit and miss trials were defined as intact trials at test receiving an 'intact' or 'rearranged' response, respectively.

Table 2.

Mean (with standard errors) of the average confidence ratings for 'intact' and 'rearranged' responses given to intact and rearranged pairs as a function of TMS target and response accuracy. The data shown here are based on data from 20 and 18 participants for correct and incorrect judgments, respectively.

Pair Type	Left Angular Gyrus	Vertex
Correct Judgments		
Intact (called Intact)	2.78 (.04)	2.79 (.04)
Rearranged (called Rearranged)	2.57 (.06)	2.57 (.06)
Incorrect Judgments		
Intact (called Rearranged)	2.30 (.08)	2.42 (.09)
Rearranged (called Intact)	2.59 (.10)	2.35 (.12)

Note. Two participants were excluded from the analysis of confidence for incorrect judgments due to having no incorrect judgments on rearranged trials. Confidence ratings for correct and incorrect judgments were analysed with separate repeated measures ANOVAs.

Table 3.

Mean proportion (with standard errors) of the three test responses to intact, rearranged, and new trials as a function of TMS target.

Trial Type	Response	Left Angular Gyrus	Vertex
Intact	Intact	.68 (.03)	.69 (.04)
	Rearranged	.24 (.02)	.23 (.03)
	New	.08 (.01)	.08 (.02)
Rearranged	Intact	.17 (.03)	.18 (.03)
	Rearranged	.65 (.04)	.68 (.04)
	New	.18 (.03)	.15 (.02)
New	Intact	.04 (.01)	-
	Rearranged	.28 (.04)	-
	New	.69 (.04)	-

Note. TMS stimulation occurred only during encoding, thus new pairs have no specific TMS target although the data are listed under Left Angular Gyrus. During the test phase, the new pairs were intermixed with intact and rearranged pairs from the Left Angular Gyrus and Vertex stimulation encoding blocks.