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Research report

The processing of semantic relatedness in the brain: Evidence from associative and categorical false recognition effects following transcranial direct current stimulation of the left anterior temporal lobe

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ABSTRACT

A dominant view of the role of the anterior temporal lobe (ATL) in semantic memory is that it serves as an integration hub, specialized in the processing of semantic relatedness by way of mechanisms that bind together information from different brain areas to form coherent amodal representations of concepts. Two recent experiments, using brain stimulation techniques along with the Deese–Roediger–McDermott (DRM) paradigm, have found a consistent false memory reduction effect following stimulation of the ATL, pointing to the importance of the ATL in semantic/conceptual processing. To more precisely identify the specific process being involved, we conducted a DRM experiment in which transcranial direct current stimulation (anode/cathode/sham) was applied over the participants' left ATL during the study of lists of words that were associatively related to their non-presented critical words (e.g., *rotten, worm, red, tree, liqueur, unripe, cake, food, eden, peel*, for the critical item *apple*) or categorically related (e.g., *pear, banana, peach, orange, cantaloupe, watermelon, strawberry, cherry, kiwi, plum*, for the same critical item *apple*). The results showed that correct recognition was not affected by stimulation. However, an interaction between stimulation condition and type of relation for false memories was found, explained by a significant false recognition reduction effect in the anodal condition for associative lists that was not observed for categorical lists. Results are congruent with previous findings and, more importantly, they help to clarify the nature and locus of false memory reduction effects, suggesting a differential role of the left ATL, and providing critical evidence for understanding the creation of semantic relatedness-based memory illusions.

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1. Introduction

The involvement of the anterior temporal lobe (ATL) in human memory functioning is now well established from a variety of sources of evidence, including computational models (McClelland & Rogers, 2003), neuropsychological (Patterson, Nestor, & Rogers, 2007) and neuroimaging studies (Visser, Jefferies, & Lambon Ralph, 2010) and, more recently, electrode-implantation studies (Shimotake et al., 2015). Of relevance here, a dominant view is that this temporal region serves as an integration hub, specialized in binding together modality-specific information from distributed brain areas, to form the coherent amodal representations that underpin concepts (Bonner & Price, 2013; Damasio, Tranel, Grabowski, Adolphs, & Damasio, 2004; Lambon Ralph, 2014; Lambon Ralph, Jefferies, Patterson, & Rogers, 2017; Patterson & Lambon Ralph, 2016; Wong & Gallate, 2012).

Consistent with its purported role as a semantic hub, the ATL is known to have connections with the temporal gyri (which receive inputs from visual, somatosensory and auditory processing streams) and the prefrontal cortex (Rogers et al., 2004). Also, damage to the ATL (as it is usually observed in semantic dementia) leads to impairments in conceptual knowledge that tend to result in generalization errors (e.g., Lambon Ralph & Patterson, 2008). In addition, a number of findings from functional neuroimaging studies fit well with this kind of involvement of the ATL in semantic aspects of cognition. Thus, it has been shown that the left ATL is more active for content (e.g., *chair*, *wall*) than function words (e.g., *in*, *under*) (Diaz & McCarthy, 2009), and that it exhibits specific significant activation when participants engage in conceptual combinations that require them to construct complex concepts (e.g., *boy*) rather than simpler ones (e.g., *male*) (Baron & Osherson, 2011).

More recently, the involvement of the ATL in semantic processing has started to be explored through non-invasive brain stimulation techniques, which allow for a different approach to understanding the relationship between brain regions and cognitive functions. By temporarily modulating cortical excitability in relatively specific brain areas (Harty, Brem, & Cohen Kadosh, 2016), these techniques allow neurocognitive researchers to test causal hypotheses about the role of particular brain regions in the behavior of neurologically intact participants, overcoming some of the drawbacks of neuroimaging and neuropsychological studies (Wong & Gallate, 2012). Brain stimulation research on the ATL has been used with a variety of experimental tasks and stimulation protocols, often making it difficult to arrive at consistent conclusions. However, the results from a few focused studies support the idea that the ATL is directly involved in semantic/conceptual processing (e.g., Lambon Ralph, Pobric, & Jefferies, 2009). Thus, for instance, temporarily disrupting neural processing in the ATL by means of repetitive transcranial magnetic stimulation (rTMS), leads to slower responses in synonym judgment tasks, with worse performance for abstract and high-order concepts than for basic ones (Pobric, Jefferies, & Lambon Ralph, 2007). Note that this is a pattern of performance that is largely comparable to that observed in people with semantic dementia (Lambon Ralph et al., 2011; Woollams, Cooper-Pye, Hodges, & Patterson, 2008).

A variety of cognitive tasks have been used to explore the involvement of the ATL in semantic processing (i.e., lexical decision, categorization, naming, decision making), all of which have contributed to provide different types of converging evidence (see for example Wong & Gallate, 2012). However, an experimental procedure that seems particularly well suited to study the role of the ATL as a semantic hub is the Deese–Roediger–McDermott (DRM) paradigm, a well-established cognitive task that is widely utilized to experimentally induce semantic-related false memories (Roediger & McDermott, 1995). In a standard DRM experiment participants are instructed to memorize, for a later test, a list of words which are associates (e.g., *table*, *sit*, *legs*, *seat* …) of a critical semantically related item (e.g., *chair*) that is never presented at study. When the participants' memory for the studied words is tested after a relatively short retention interval, they usually produce or endorse the critical item as a previously presented word, a memory illusion that has been shown to depend on the semantic relatedness between studied words and critical items. Experimental manipulations that normally favor the processing of the semantic features of the studied words [e.g., deep processing (Thapar & McDermott, 2001); list blocking (Tussing & Greene, 1997); relational processing (McCabe, Presmanes, Robertson, & Smith, 2004); or elaborative rehearsal (Read, 1996)] have shown to increase false memory effects (higher rates of recall and recognition of critical items). It is also the case that participants such as children, who display poor abilities at a variety of semantic tasks early in their development, tend to show lower rates of false memory in this paradigm (Brainerd, Reyna, & Ceci, 2008; Carneiro & Fernandez, 2010; Carneiro, Albuquerque, Fernandez, & Esteves, 2007). In addition, the characteristics of false memory effects in the DRM paradigm have proven to be of relevance for understanding semantic processing in connection with certain cognitive impairments. Thus, different types of brain damage have been related to false memory modulation in amnesic patients (e.g., Schacter, Verfaellie, & Anes, 1997; Schacter, Verfaellie, Anes, & Racine, 1998; Schacter, Verfaellie, & Pradere, 1996; Van Damme & D'Ydewalle, 2009), or Alzheimer's disease (e.g., Budson, Daffner, Desikan, & Schacter, 2000; Budson et al., 2002). Interestingly, there is evidence that atypical ATL functioning is associated with reduced false memories in DRM procedures. Thus, for example, patients with ATL damage (i.e., those with a diagnosis of semantic or fronto-temporal dementia), have been found to exhibit not only impaired performance in semantic memory tasks, but also lower rates of false recognition (e.g., Simons et al., 2005; de Boysson et al., 2011).

Of especial relevance here, two separate brain-stimulation studies found that altering ATL activity leads to lower rates of false recognition (Boggio et al., 2009; Gallate, Chi, Ellwood, & Snyder, 2009). Gallate et al. (2009) hypothesized that if the ATL is involved in the formation of false memories by virtue of the "semantic" attributes shared among the studied words, inhibiting the activity of the ATL through rTMS would reduce the probability of falsely recognizing critical items. Their results were consistent with that hypothesis, showing that disrupting ATL activity did not affect correct recognition, but substantially reduced false memory rates. In a similar vein, Boggio et al. (2009) found a false memory reduction when their participants studied and recognized DRM lists while their ATL received anodal transcranial direct current stimulation (tDCS), a non-invasive brain stimulation technique that induces transient changes in cortical excitability by means of weak electric currents applied to the scalp.[1]

In summary, distinct findings from a variety of studies using the DRM paradigm seem to converge to suggest a role of the ATL in the creation of semantic illusions, even though the precise mechanisms underpinning such a role remain to be established.

A recent study by Chadwick et al. (2016) has suggested a specific way whereby the ATL might modulate the production of false memories in situations such as those represented by DRM-like procedures. In their study, they aimed to test the hypothesis that the ATL contains similarity-based codes (neural codes of the semantic overlap between the lists of studied items and their critical lures) that would directly relate to the likelihood that the word lists generate false memories. By using fMRI and representational similarity analyses to obtain measures of neural overlap, Chadwick et al. (2016) showed that the only significant cluster of positive correlations between neural overlap and the likelihood of a DRM illusion (the measure of the latter taken from canonical false-recognition scores) was in the left ATL. Hence, concrete patterns of ATL activity, assumed to reflect the degree of semantic similarity between concepts, were able to successfully predict false recognition, providing empirical support for the idea that the ATL plays a critical role in the formation of semantically-driven memory illusions acting as an amodal semantic hub (Lambon Ralph, Sage, Jones, & Mayberry, 2010; Patterson & Lambon Ralph, 2016; Wong & Gallate, 2012).

The findings by Chadwick et al. (2016) represent a significant step forward towards understanding the involvement of the ATL in semantic processing and the nature of semantic representations. Moreover, they allow for the formulation of new fine-grained hypotheses, and they are suggestive of the use of complementary methodological procedures that could provide further convergent evidence for the role that the ATL may play in false memory formation and, more generally, in semantic processing. By the nature of their study, the conclusions by Chadwick et al. are based on correlational evidence, and they could be greatly strengthened by convergent evidence obtained from direct manipulations of the ATL activity in a controlled experimental setting. In this regard, an interesting possibility is the use of non-invasive brain stimulation techniques that can temporarily interfere with normal ATL functioning in healthy participants.

As mentioned earlier, two previous studies have used non-invasive brain stimulation in conjunction with the DRM paradigm (Boggio et al., 2009; Gallate et al., 2009). In both studies, the stimulation of the ATL led to a reduction of false memories, which is consistent with the role attributed to the ATL in the literature reviewed above. However, these two brain stimulation studies were not specifically aimed at studying the nature of the ATL involvement in false memory production, and their memory protocols diverge from standard DRM procedures in ways that make fine-grain conclusions difficult to reach. Thus, for example, the use of a very small number of word lists, the absence of detailed information on the criteria used to create the word lists, the assignation of multiple critical words for each list, or the low false memory rates observed, place these otherwise valuable studies far from being an appropriate benchmark for Chadwick et al.'s (2016) proposal about the functions of the ATL.

With the aim of putting to a strong empirical test the assumption that the ATL functions as an integration hub, and capitalizing on the idea that the DRM paradigm is an adequate procedure for studying semantic memory mechanisms, we conducted a memory experiment with strictly controlled materials and conditions, in which tDCS (anodal/cathodal/sham) was applied over the participants' left ATL during the study of DRM lists. Closely following standard DRM procedures, multiple lists of words were used. Of special relevance, a subset of the lists was *associative* in nature (each composed by a well-defined set of strong associates of the non-presented critical word according to free-association norms), and the other subset was composed of *categorical* lists (formed by exemplars belonging to the same taxonomic category as the non-presented critical word). The rationale behind the introduction of categorical in addition to associative lists was to establish a dissociation procedure to more precisely investigate the false memory reduction associated with ATL activity. Both associate and categorical DRM lists are known to induce memory illusions, even though on the basis of recent experimental dissociations (Carneiro, Garcia-Marques, Lapa, & Fernandez, 2016; Coane, McBride, Termonen, & Cutting, 2016) there is ground to assume different mechanisms in each case. The putative effects of tDCS over the ATL during the memory-encoding phase could have differential effects depending on the “semantic” nature (categorical or associative) of the DRM lists. The dissociation procedure implemented by the use of the two types of lists would allow us to test two different semantic contexts for the same word (and therefore two different meanings of the same word), which could shed light into the role of the ATL in different semantic-memory tasks and, more specifically, to provide additional evidence that diverse neurocognitive mechanisms may underlie different types of semantically-related false memories.

More specifically, if the ATL plays a determinant role in conceptualization by letting varied experiences merge into an amodal semantic representation (Pobric, Jefferies, & Lambon Ralph, 2010), a more central role of this brain region is expected during the processing of episodic events such as associative lists. This could be the case because associative lists contain elements connectable through a variety of possible relations and therefore more arduous to integrate into a coherent concept, relative to the processing of a list of high-dominance category members, which are connectable along the simpler and more homogeneous relation defined by the label of the category. Following this rationale, the prediction for the present study was that tDCS of the left ATL would lead to the modulation of the false recognition of non-

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[1] At the neuronal level, anodal stimulation generally increases membrane excitability (and spontaneous firing rate) whereas cathodal stimulation tends to exert the opposite effect (Romero Lauro et al., 2014).

presented words related to the studied lists,[2] with such effect being larger for associative lists than for categorical ones. In addition, and based on results reported by Boggio et al. (2009), who only applied anodal tDCS over the left ATL, we expected such a tDCS-induced modulation to be observed, at least, for the anodal group.

2. Method

Adhering to open-science procedures, we report in this and in the following section how we determined our sample size, all data exclusions, all manipulations, and all measures collected in the study.

2.1. *Participants*

Sixty-nine undergraduate students from the University of Jaén were recruited to participate voluntarily in the experiment, in exchange for course credit. None of them reported to suffer from epilepsy (nor having close relatives affected), migraines, brain damage, cardiac disease, or other psychological or medical condition. All participants were right-handed, according to the Edinburgh Handedness Inventory (Oldfield, 1971), and were randomly assigned to one of the three experimental conditions. Upon arrival to the laboratory, participants were informed about the general aim of the study and signed an informed consent form. No precise information regarding the experimental hypotheses was facilitated to the participants until they completed the experiment. The ethical committee of the University of Jaén approved the study. The lower limit of the sample size was established in advance to be at least double the most similar published study (Boggio et al., 2009; n = 10 participants by stimulation condition) and in the range of those used in standard DRM experiments. The upper limit of the sample size was also set ahead of time, and the goal was testing as many participants, over the minimum of 20, as permitted by the availability of laboratory sessions with the target sample of volunteers. As a result, the testing plan included running 69 sessions, 23 in each stimulation condition.

Four participants were eliminated from the study for failing to meet the accuracy criterion set for the recognition task. A non-parametric measure of bias (B''_D) was calculated for each subject, and participants having scores above or below 1.96 * 1 SD of the bias mean were excluded from analyses. The bias for correct recognition was used as criteria for outlier detection based on results from Kantner and Lindsay (2012), who showed that response bias could be seen as a trait-like predisposition, with substantial within-individual consistency. This criterion was established as a way to exclude possible extreme response patterns (e.g., subjects not following procedure instructions), and ensuring the use of measures (hit rate and false alarm) that would not be used at all to test the main hypothesis. The threshold of 1.96 * SD was established to exclude extreme 5% scores. A total of 65 participants (anodal n = 22; cathodal n = 21; and sham n = 22) were included in the final sample (48 female and 17 male, mean age 20 years, age range 17–29 years).

2.2. *tDCS*

A CE-certified battery-driven stimulator (neuroConn DC-STIMULATOR) was used to conduct non-invasive tDCS with an intensity of 2 mA. Two 5 × 7 cm rubber electrodes covered with saline-soaked sponges were used to transfer constant direct current, resulting in a density of .06 mA/cm^2. In the anodal condition, the anode was placed over site FT9[3] (BA 38/20), according to the International 10-10 System for EEG electrode placement, and the cathode was placed extracranially, over the right shoulder, to minimize its effects over the brain. In the cathodal condition, the cathode was placed over site FT9 and the anode was placed over the right shoulder. The stimulation application time was 20 min and was faded in and out with an 8 sec ramp. The stimulation time was established on the basis of previous tDCS studies (i.e., Zwissler et al., 2014), considering the duration of the presentation of the experimental items for encoding and the duration of the filler tasks to be performed right before and right after encoding the lists. During the sham tDCS condition, the same fade in/fade out ramp was applied but the constant current lasted only 30 sec.

2.3. *Design*

A mixed factorial design 3 (2 × 4) was used, with type of stimulation (anodal, cathodal or sham) as the between-participants factor, and type of relation (associative or categorical) and type of item (studied, critical, control critical or distractor) as the within-participant factors. False alarm rates (for false recognition) and hit rates (for correct recognition) were the dependent variables, even though composite measures from these variables were also used for analyses derived from the signal detection theory (Donaldson, 1992).

2.4. *Stimuli*

Twenty-four critical words that were the most frequent exemplars in their category according to normative data in Spanish (Marful, Díez, & Fernandez, 2015) were used in this experiment. Two different lists of words were created for each of these critical items (see Table 1 for a representative example, and the Appendix for the complete set of verbal materials, in Spanish and their English translation). One was a categorical list formed by 10 words that belonged to the same category as the corresponding critical lure (the most frequent items in the category after it). The other was an associative list, consisting of the 10 strongest associates of the critical word, according to backward association strength (BAS) values obtained from Spanish free-association norms (Fernandez, Díez, & Alonso, 2014; Fernandez, Díez, Alonso, &

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[2] Although the main measures in the experimental task are based on a word recognition paradigm, the underlying processes are not necessarily restricted to words, lexical networks or judgments about words, since false recognition in DRM paradigm is typically interpreted in terms of gist-based illusions.

[3] FT9 is considered the closest electrode to the left anterior temporal pole (e.g., Acharya, Hani, Thirumala, & Tsuchida, 2016).

Table 1 – Example of associative and categorical word lists for the critical word apple, in their English translation.

Associative	Critical word	Categorical
Rotten	**Apple**	Pear
Worm		Banana
Red		Peach
Tree		Orange
Liqueur		Cantaloupe
Unripe		Watermelon
Cake		Strawberry
Food		Cherry
Eden		Kiwi
Peel		Plum

Beato, 2004), with the exclusion of words that belonged to the same semantic category as the critical ones.

To better characterize the differences in the underlying relational structure of the two types of lists, a number of values related to associative strength, connectivity and categorical properties were calculated for the 48 lists. Associative strength and connectivity are measures derived from free association norms, and they are usually estimated as the proportion of participants in a sample who produce a specific word (target) as a response to another word (cue) in a free association task (Nelson, McEvoy, & Dennis, 2000), in the case of associative strength, or as a count of the words that have an association strength greater than zero, in the case of connectivity. Several measures using strength or connectivity have shown to be related to the performance of human participants in memory tasks. For example, memory research has shown superior recognition for words with high connectivity, high number of resonant connections, and high resonance strength (Nelson, Zhang, & McKinney, 2001). Associative strength is also an important variable in false memory production (Gallo, 2006) and, for example, backward association strength (BAS) has been identified as a strong predictor of false memories when other variables (e.g., forward association strength [FAS]), word length, word frequency, concreteness or connectivity are controlled (Roediger, Watson, McDermott, & Gallo, 2001).

We computed four different measures derived from association strength between list words: BAS (the mean value of the strength of backward association from the 10 list words to the critical word); FAS (the mean value of the strength of forward association from the critical word to the 10 words in the list); resonance strength (RSG: the weighting of the bidirectional connections between the critical word and the list words, obtained by cross-multiplying the forward by the backward strength of the association between each list word and the critical word, and summing the 10 values); overlapping strength (OSG: the sum of the cross-multiplications of the association strength between common associates to list words and the critical word). And five measures related to the number of connections between the list words and the critical words: number of resonant connections (NRC: the number of bidirectional connections between the critical word and the list words); mean connectivity (MC: the number of interconnections between the list words); number of mediated connections (NMED: the number of mediated connections linking the critical word and list words); mean set size (MSS: the mean number of free associates of list words); accessibility of list words (ACC: a numerical index that reflects how easily a word is generated as a response in a free association task). Also, to obtain an estimation of potential interactions among words in the lists, we calculated the expected critical word activation for each list under the assumptions of two different models, an activation-at-a-distance model (AD-M) and a spreading-activation model (SA-M), using the equations described by Nelson, McEvoy, and Pointer (2003). These equations allowed us to compute a single value that represents the estimated critical lure activation. The distance model predicts that total connections, not their direction, are important, assuming that the activation of word-to-word connectivity and word-to-critical resonant links increase the activation of the critical item. The spread-activation model predicts that connections among the studied words will have a greater effect on memory when more of those words return activation; so, the effects of word-to-word connectivity would be contingent on the number and strength of resonant connections that allow the activation to return to the critical word.

The internal structure of categories has also been related to accurate and false recall and recognition (Nosofsky, 1988; Smith, Ward, Tindell, Sifonis, & Wilkenfeld, 2000). For that reason, three measures were calculated from a set of Spanish category norms (Marful et al., 2015): mean frequency of production of list words as category exemplars (CFREQ); mean rank, determined by output position of list words in their category (CRANK); and mean lexical availability of list words in the category (LAC: a numerical index reflecting how easily an exemplar is generated as a member of a category).

The average values for all the indexes in the two types of list (associative and categorical) are presented in Table 2. It is worth noting that the associative lists had higher BAS, MRSG and NRC values than the categorical ones, while the categorical lists had more connections among the list words (MC), higher overlapping strength between list words and the critical word (OSG), more mediators (NMED) and larger set sizes (MSS) than the associative lists.

As shown in the examples in Fig. 1, in associative lists words are directly (i.e., NRC) and highly (i.e., BAS) connected to their critical word, the critical words tend to receive more connections than the rest of words, and there are a variety of conceptual relationships between the words in the network. In categorical lists, words are highly connected among themselves (i.e., CON), connected with the critical words through mediators (i.e., NMED), the critical words are not always the words that receive more connections, and the relations between words can be explained by their membership to a common category (*fruits* in the example).

For each participant, the starting pool of 24 critical words and their related word lists was divided into two sets: one set with 16 critical words and their lists to be used as study materials, and another set with the remaining 8 critical words and their lists to be used as distractor and control material in the final recognition test. Each participant was therefore presented with 16 lists of words at study, half of them associative and the other half categorical. The assignment of the pool of 24 critical words and their related lists to the study or control sets, and the associative or categorical relation in the

Table 2 – Average values for structural characteristics in associative and categorical lists. The critical word was the same for both types of list.

	Associative	Categorical	Sig difference
	M (*SD*)	*M* (*SD*)	
Backward association (BAS)	.21 (.16)	.08 (.06)	***
Forward association (FAS)	.04 (.03)	.06 (.12)	
Resonance strength (RSG)	.05 (.06)	.02 (.05)	*
Overlapping strength (OSG)	.01 (.01)	.02 (.02)	*
Number of resonant connections (NRC)	4.83 (2.20)	3.04 (2.22)	*
Mean connectivity (CON)	1.08 (.76)	2.35 (1.17)	**
Number of mediators (NMED)	6.47 (2.81)	9.35 (5.33)	**
Mean set size (MSS)	14.48 (3.45)	18.74 (9.03)	*
Accessibility index (ACC)	35.09 (22.92)	53.42 (50.17)	
Activation-at-a-distance model (AD-M)	2.72 (1.66)	1.54 (.88)	*
Spreading-activation model (SA-M)	.05 (.06)	.02 (.05)	*
Frequency of Categorical production (CFREQ)	15.28 (12.73)	81.73 (25.29)	***
Rank in categorical production (CRANK)	6.34 (1.16)	5.92 (.74)	
Lexical availability in the category (LAC)	2.79 (2.98)	15.61 (4.66)	***

Probability in Wilcoxon signed rank tests: *p < .05 **p < .01 ***p < .001.

study conditions, were counterbalanced to ensure that every list was presented in all the different conditions throughout the experiment.

2.5. *Procedure*

A personal data form and a questionnaire to screen for exclusion conditions were administered first, and all participants signed out an informed consent form before performing the experimental tasks. After electrode placement, and as the stimulation started, all participants were asked to do a visual search task that consisted of searching and circling specific letters (“n”, “p” and “c”) on a sheet of paper with a text written in a language (Polish) that was not familiar to any of them. After 7 min, which constitutes the idle time, the visual search task was interrupted and the participants were asked to follow experimental instructions on the computer screen. The participants were informed that they would listen to 16 lists of words followed by some mathematical operations that they would have to check for accuracy, and that they would later perform a final memory test on the words presented in the lists. Following standard DRM procedures, the study lists were presented aurally, over external speakers, with words presented 2 sec apart. This presentation format has been shown to provide reliable high levels of false recognition on visual memory tests (for a review, see Gallo, 2006). The 16 study lists were organized in a pseudorandom order for each participant, which involved two groups of 8 lists and, within each group, 4 associative lists and 4 categorical lists, distributed randomly. The words within each list kept always the same order, from greater to lesser frequency of categorical production or associative strength.

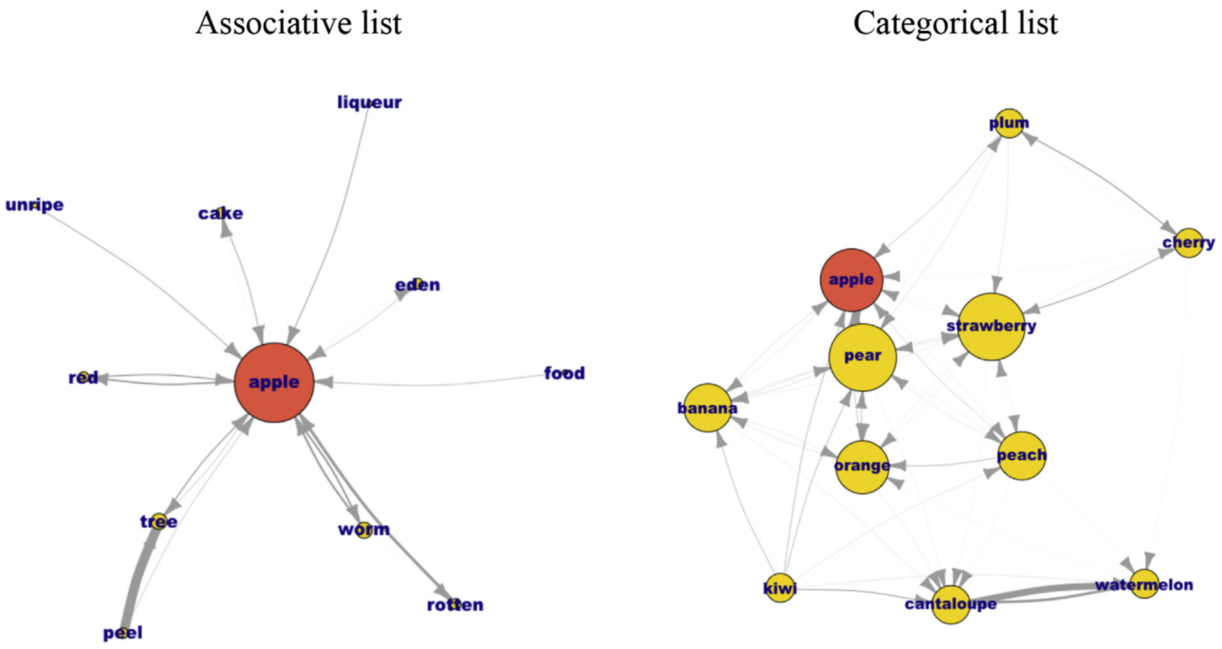

Fig. 1 – An example of differences between associative and categorical lists for the critical lure *apple*. The red node represents the non-presented critical item and the yellow nodes represent the studied items. The size of the node for each word is proportional to the number of associative connections received from the other nodes; the line width is proportional to the association strength; the arrows indicate the direction of the associations. Network representations created with *igraph* (Csardi & Nepusz, 2006).

Immediately after the presentation of the 16 lists, a distracting task was to be performed for 2 min, with participants required to check whether a series of simple mathematical operations were correct or not. Following this task, the participants did the final memory test, preceded by appropriate instructions. Importantly, the stimulation time always finished before the start of the memory test. This test was a yes/no recognition task which included 64 words: the 16 critical words of the studied lists (8 associative and 8 categorical), 8 critical words from similar non-presented lists (control critical words), 32 studied words (those in positions 2 and 7 from each studied list), and 8 distractors from the non-presented lists (the word in position 2 of each unstudied list). At test, the words were shown one by one on the center of the computer screen, following a random sequence that was unique for each participant. A fixation point lasting for 750 msec preceded each word, which remained on the screen until a response was given on the keyboard. After completing the recognition task, participants were thanked for their collaboration, debriefed with a short explanation of the experimental procedure and advised not to discuss the experiment with other potential participants. Stimuli presentation and response recordings were controlled by E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA). Fig. 2 shows a general outline of the procedure.

3. Results

Table 3 shows average recognition rates for all conditions and item types. Overall, a strong false recognition effect was observed across stimulation conditions, denoted by higher recognition rates for critical words in comparison to the recognition rate of non-related distractor words.

3.1. *Correct recognition*

Fig. 3 depicts the data for correct recognition. A 3 (stimulation condition: Anodal *vs* Cathodal *vs* Sham) × 2 (type of relation: Associative *vs* Categorical) mixed ANOVA on hit rates ("yes" responses to studied words) revealed a statistically significant effect of type of relation [$F(1,62) = 19.68$, $MSE = .02$ $p < .001$, $\eta_p^2 = .24$, 90% CI [.10, .37], $\eta_G^2 = .10$]. On average, studied words from categorical lists ($M = .78$; $SEM = .02$) were better recognized than those from associative lists ($M = .67$; $SEM = .02$). No other source of variability reached statistical significance (both stimulation condition and the interaction with $F < 1$), showing that the advantage of categorical lists over associative lists was not modulated by tDCS.

For completeness, we also performed non-parametric signal-detection analyses, computing A′ and B''_D values (Donaldson, 1996; Stanislaw & Todorov, 1999). A′ is the non-parametric version of d' and it provides a measure of discriminability varying from 0 to 1, with .5 indicating chance performance. B''_D provides a bias estimate, with values greater than 0 indicating conservative bias and lesser than 0 indicating liberal bias. The 3 × 2 ANOVA on A' showed the effect of type of relation to be the only reliable, [$F(1,62) = 7.70$, $MSE = .01$ $p < .01$, $\eta_p^2 = .11$, 90% CI [.02, .24], $\eta_G^2 = .03$], with participants exhibiting higher sensitivity when responding to categorical lists ($M = .89$; $SEM = .01$) than to associative lists ($M = .86$; $SEM = .01$). Neither stimulation condition ($F < 1$) nor the interaction reached statistical significance [$F(2,62) = 1.65$, $MSE = .05$, $p = .20$, $\eta_p^2 = .05$, 90% CI [0, .14], $\eta_G^2 = .01$]. The

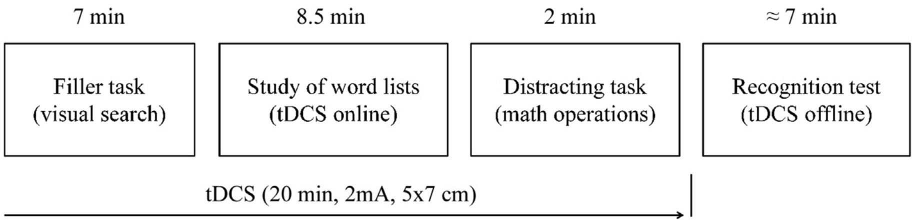

Fig. 2 – General outline of the procedure.

Table 3 – Mean recognition results (SD) as a function of type of relation and type of stimulation.

	Associative			Categorical		
	Anodal	Cathodal	Sham	Anodal	Cathodal	Sham
Studied words						
Correct recognition	.70 (.13)	.67 (.20)	.66 (.16)	.79 (.18)	.78 (.15)	.77 (.16)
Sensitivity (A′)	.87 (.07)	.87 (.07)	.83 (.16)	.89 (.09)	.89 (.11)	.90 (.06)
Bias (B''_D)	.20 (.18)	.21 (.27)	.20 (.18)	.08 (.23)	.09 (.21)	.09 (.24)
Critical words						
False recognition	.46 (.22)	.56 (.26)	.67 (.27)	.58 (.28)	.66 (.22)	.59 (.20)
Sensitivity (A′)	.76 (.17)	.80 (.15)	.84 (.16)	.82 (.12)	.85 (.11)	.83 (.08)
Bias (B''_D)	.43 (.20)	.32 (.31)	.18 (.32)	.29 (.35)	.21 (.28)	.27 (.28)
Distractors						
False alarms	.06 (.11)	.06 (.11)	.14 (.20)	.12 (.17)	.11 (.19)	.14 (.17)
Critical control	.16 (.20)	.18 (.21)	.16 (.23)	.14 (.15)	.15 (.23)	.12 (.23)

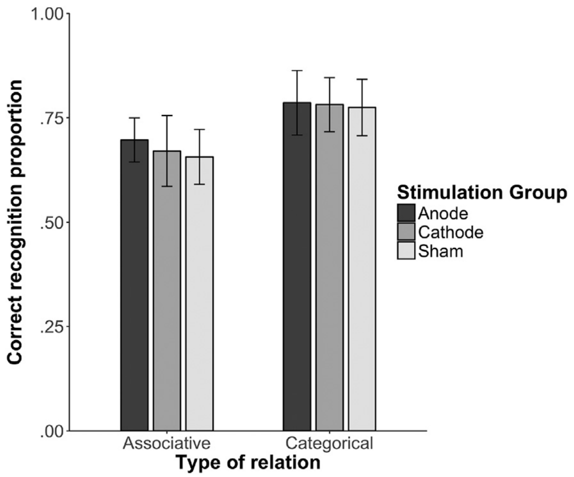

Fig. 3 – Correct recognition as a function of Stimulation and List type. Error bars represent 95% confidence interval (CI).

analysis on B″$_D$ also revealed a significant effect of type of relation [$F(1,62) = 12.56$, $MSE = .03$, $p < .001$, $\eta_p^2 = .17$, 90% CI [.05, .30], $\eta_G^2 = .06$], whereby participants were more conservative with associative lists ($M = .20$; $SEM = .03$) than they were with categorical lists ($M = .09$; $SEM = .05$). The remaining effects did not reach statistical significance (Fs < 1).

3.2. False recognition

The data for false recognition is depicted in Fig. 4. A 3 (stimulation condition: Anodal *vs* Cathodal *vs* Sham) × 2 (type of relation: Associative *vs* Categorical) mixed ANOVA on false recognition rates ("yes" responses to critical words) failed to show significant main effects [stimulation condition: $F(2,62) = 2.02$, $MSE = .08$, $p = .14$, $\eta_p^2 = .06$, 90% CI [0, .16], $\eta_G^2 = .04$; type of relation: $F(1,62) = 1.81$, $MSE = .04$, $p = .18$, $\eta_p^2 = .03$, 90% CI [0, .12], $\eta_G^2 = .01$]. However, there was a reliable interaction between stimulation condition and type of relation, [$F(2,62) = 3.33$, $MSE = .04$, $p = .04$, $\eta_p^2 = .10$, 90% CI [.001, .20], $\eta_G^2 = .03$] that we followed up through an one-way ANOVA for each type of relation. These analyses revealed that stimulation condition had an effect on false recognition for associative lists [$F(2,62) = 3.85$, $MSE = .06$, $p = .03$, $\eta_p^2 = .11$, 90% CI [.007, .22], $\eta_G^2 = .11$], but not for categorical lists [$F(2,62) = .834$, $MSE = .05$, $p = .44$, $\eta_p^2 = .03$, 90% CI [0, .10], $\eta_G^2 = .02$]. Tukey's test (Keppel & Wickens, 2004) showed that false recognition for associative lists was significantly lower in the anode group ($M = .46$; $SEM = .05$) than in the sham group ($M = .67$, $SEM = .06$) ($p < .05$, $d = -.85$, 95% CI [−1.49, −.22]).

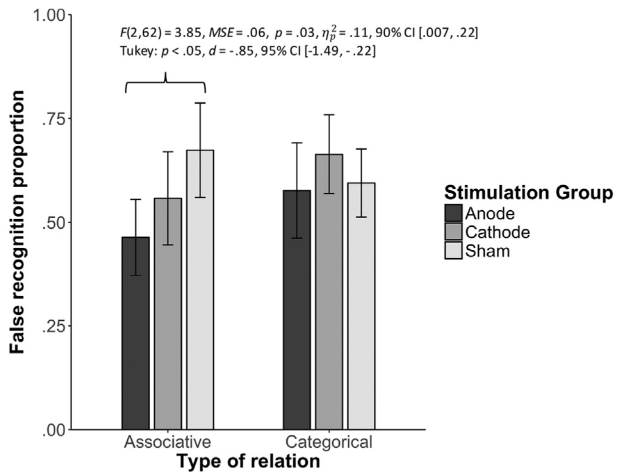

Fig. 4 – False recognition as a function of Stimulation and List type. Error bars represent 95% confidence interval (CI).

Non-parametric signal detection analyses showed no significant effects on sensitivity [stimulation condition: $F(2,62) = 1.06$, $MSE = .02$, $p = .35$, $\eta_p^2 = .03$, 90% CI [0, .11], $\eta_G^2 = .02$; type of relation: $F(1,62) = 2.35$, $MSE = .01$, $p = .13$, $\eta_p^2 = .04$, 90% CI [0, .14], $\eta_G^2 = .01$; interaction: $F(2,62) = .98$, $MSE = .01$, $p = .38$, $\eta_p^2 = .03$, 90% CI [0, .11], $\eta_G^2 = .01$], but a statistically significant interaction between stimulation condition and type of relation on response bias was found [$F(2,62) = 3.52$, $MSE = .05$, $p < .05$, $\eta_p^2 = .10$, 90% CI [.004, .21], $\eta_G^2 = .03$]. A one-way ANOVA for each type of relation confirmed that stimulation condition had an effect on response bias for associative lists [$F(2,62) = 4.43$, $MSE = .08$, $p = .02$, $\eta_p^2 = .12$, 90% CI [.01, .24], $\eta_G^2 = .03$], but not for categorical lists [$F(2,62) = .49$, $MSE = .09$, $p = .62$, $\eta_p^2 = .02$, 90% CI [0, .07], $\eta_G^2 = .02$]. Tukey's test showed that responses were more conservative ($p < .05$, $d = .94$, 95% CI [.3, 1.58]) to associative critical words in the anode group ($M = .43$; $SEM = .04$) than they were in the sham group ($M = .18$; $SEM = .07$).

3.3. False recognition as a function of stimulation type, type of relation, and associative relatedness (strength and connectivity)

A false recognition score was calculated for each critical lure in the two types of lists (associative and categorical) and in the three stimulation conditions (anodal, cathodal and sham). This was possible here because the assignment of the 24 critical words to the experimental conditions was counterbalanced, ensuring a minimal and comparable number of observations for each critical lure in all conditions across the experiment.

Then, the false recognition scores in all conditions were entered into correlational analyses (family-wise error rate controlled with Bonferroni-Holm method) along with some of the associative structural features described in Table 2, namely, those related to associative strength and connectivity. Fig. 5 shows the correlograms representing Spearman's rank correlations among observed false recognition and the features reflecting the underlying relational structure of the word lists.

To test for differences in the predictive value of the variables with significant correlations (NRC, AD-M and SA-M), we performed a mixed-effects regression model analysis guided by the pattern of significant correlations. For each variable, a model with the interaction of stimulation and type of relation as fixed factors was compared with another model in which the variable was added as the third term of the interaction, using subjects (critical words/lists in this case) as a random effect. The Likelihood Ratio Tests showed a significant value for the three variables [NRC: χ^2 (6) = 27.57, $p = .0001$; AD-M: χ^2 (6) = 31.29, $p = .00002$; SA-M: χ^2 (6) = 13.38, $p = .037$; respectively] showing that a triple interaction model is a good fit for

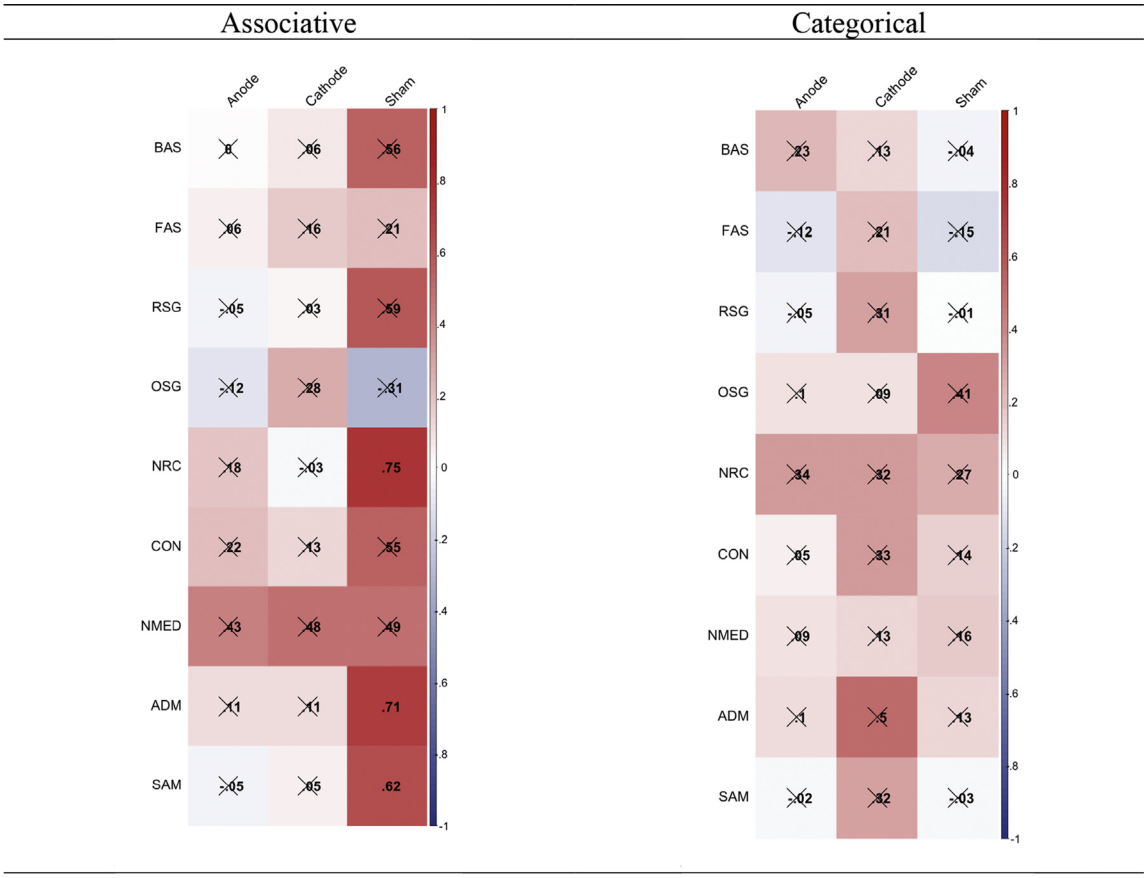

Fig. 5 – Correlograms representing Spearman's rank correlations among false recognition and features related to the relational structure of the word lists, by type of relation and stimulation condition. Intensity and color of squares represents the magnitude and sign (red = positive and blue = negative) of the correlation, respectively. A crossed value indicates a non-significant correlation ($p > .05$; Bonferroni-Holm). (BAS: Backward Association Strength; FAS: Forward Association Strength; RSG: Resonance Strength; OSG: Overlapping Strength; NRC: Number of Resonant Connections; CON: Mean Connectivity among list words; NMED: Number of Mediators; AD-M: False recognition predicted by an activation-at-a-distance model; SA-M: False recognition predicted by an spreading-activation model).

the data. To explore the interactions, three separate similar mixed effects analyses were performed for each type of relation, excluding cathode stimulation data due to the interest in testing the relevance of the three variables only for the conditions in which a difference was observed in the main analysis (anode < sham). Analyses showed significant differences between Anode and Sham conditions for the three variables in the associative lists, but no differences between those stimulation conditions for categorical lists (see Table 4).

4. Discussion

The main finding in this study was the differential effect that tDCS of the left ATL had on false memory creation. A substantial reduction of false memories was observed after anodal stimulation, relative to sham, with word lists composed of strong associates of the critical words, but no effect at all emerged when lists were composed of exemplars belonging to the same taxonomic category as the critical lures. A number of points deserve further discussion and are addressed in what follows.

Table 4 – Results of Likelihood Ratio Tests comparing the difference in the predictive value of the variables between Anode and Sham conditions for each type of relation.

Variable	Associative	Categorical
NRC	χ^2 (2) = 18.00, p = .0001	χ^2 (2) = 4.28, p = .12
AD-M	χ^2 (2) = 15.49, p = .0004	χ^2 (2) = .41, p = .81
SA-M	χ^2 (2) = 9.66, p = .008	χ^2 (2) = .38, p = .83

In line with an extensive set of laboratory studies conducted in the last two decades (Gallo, 2006, 2010), memory illusions induced by semantic relatedness were reliable in the sham group with both associative and categorical materials, illustrating once again how semantic and episodic systems closely interact in memory-demanding situations. And consistent with a more limited set of studies (Boggio et al., 2009; Gallate et al., 2009), the present results converge on showing that modulating neural activity in the left ATL modifies the pattern of false recognition in the absence of any variation in correct recognition. Furthermore, in what can be seen as a novel contribution to the field, we show for the first time a straightforward dissociation of the effect of tDCS over the left ATL, since stimulation differentially affected the production of association-based false memories while leaving unaffected the production of category-based false memories. In our view, such a specificity of the effect of stimulation provides finer-grade evidence of the involvement of this brain area in semantic processing and, more specifically, in the creation of semantic relatedness-based memory illusions. Specifically, this finding is suggestive of how the left ATL may function as an integration hub when processing associatively related verbal materials in the context of episodic learning, enabling the indirect activation of conceptual representations that are not actually processed, but have overlapping features with the items presented for studying.

In terms of current accounts of false memory effects in list-learning paradigms, the results are in line with views that assume that during the encoding of word lists, participants establish a well-integrated conceptual network, with reactivation of that integrated network during retrieval leading to false recall and recognition (Meade, Watson, Balota, & Roediger, 2007). As stated in the introduction, in this experiment the relational composition of half of the lists (the associative ones) was more likely to require the active role of the ATL while encoding than the other half (the categorical ones). And precisely, the false recognition reduction effect was only found for these associative lists, which might be interpreted as if anodal stimulation during encoding had interfered with the establishment of the integrated conceptual network that would make possible the activation of the concept corresponding to the critical word.

To further substantiate this interpretation, we also performed correlational analyses between the false memory scores for the critical items and several features that characterize the semantic relatedness among list items or between list items and their critical items, followed by mixed-effects regression analyses to confirm the differences in the observed correlations between conditions (see Fig. 5). Some researchers have linked false recognition with different features of DRM lists related to the number, strength or direction of the connections among their words (e.g., Knott, Dewhurst, & Howe, 2012; McEvoy, Nelson, & Komatsu, 1999). As some of these features have been found to modulate false recognition (e.g., backward associative strength from list words to the critical word, or mean connectivity among list words), the exploration of how false recognition is associated with those features across stimulation conditions can clarify the nature of the effects found in this experiment.

Two main ideas emerge from the performed analyses. First, there are some clear differences in the pattern of correlations for the two types of lists in the group without stimulation (Sham). For associative lists, reliable and higher correlations are especially observed in features that are related to both the density of connections of the network linking list words to the critical word and to the strength of those connections. The highest correlation concerned the number of resonant connections ($r = .75$), indicating that lists with more words producing the critical word as an associate were more likely to trigger false recognition in the memory test. Measures of predicted critical word activation (i.e., AD-M and SA-M) also showed that both total connections of the network and return of activation from the associates were highly correlated with false recognition. In contrast, for categorical lists the correlation pattern was very different, with no correlations reaching significance. Because categorical lists led to high rates of false recognition, it is worth noting here that these findings, in the Sham group, reinforce the basic assumption that false recognition for associative and categorical lists could arise from different kinds of processes.

Second, and more interestingly for the present study, there are also clear correlational patterns associated with particular stimulation conditions and types of relation that help to clarify the effects of tDCS, as well as the interaction between stimulation and type of relation found in the experiment. Consistent with the findings of the mixed effects regression analyses, in the case of associative lists the main feature of the correlational patterns is that the reliable correlations for some of the strength and connectivity features (NRC, AD-M, SA-M) observed in the sham condition disappeared with anodal stimulation. This result could be interpreted as if anodal stimulation over the left ATL had a negative effect on the connectivity between studied and critical items (NRC). Furthermore, the two measures used to estimate the degree of activation of the critical word (AD-M and SA-M), and found to have high and reliable correlations with false recognition in the sham condition, did not show those reliable correlations in the anodal condition. In summary, semantic relatedness-based memory illusions were differentially affected by anodal stimulation, which appears to limit the processes underlying the establishment of an integrated conceptual network during the encoding of associative lists, the ones with more variety in conceptual links and with higher number of strong associative links among studied and critical items.

These results are consistent with distributed-plus-hub views of the ATL (Patterson & Lambon Ralph, 2016; Patterson et al., 2007) and could reflect the functioning of a convergent architecture that collects information from both direct and indirect nodes. Even more specifically, the particular pattern of false recognition responses, characterized by a decrement in associative false memories when the activity of the left ATL was modulated by tDCS, can be taken as evidence that is in convergence with the recent finding that neural overlap in the left ATL is a reliable predictor of DRM illusions (Chadwick et al., 2016).

The present account of the effects is necessarily tentative, and it would obviously benefit from further exploration of the conditions under which semantic processing of various kinds are likely to influence performance in memory tasks of the kind employed here and other tasks and paradigms (e.g., with non-linguistic materials). The fact that the left ATL has been shown to play such a relevant role does not mean that other areas in the temporal cortex or elsewhere in the brain (see recent evidence by Ramirez et al., 2013, on the hippocampus; Berkers et al., 2017; Warren, Jones, Duff, & Tranel, 2014, on the frontal lobes; or McDermott, Gilmore, Nelson, Watson, & Ojeman, 2017 on parietal involvement) cannot contribute to semantically-based memory illusions in a number of ways; extending stimulation procedures to brain regions already identified as potentially involved, on the basis of prior lesion and neuroimaging results (Dennis, Bowman, & Turney, 2015;

Schacter & Slotnick, 2004) would strengthen a convergent-evidence approach that could lead to progress into developing better explanations of the processes. It would also be important to design further experiments that incorporate stimulation schedules that could be more in synchrony with the assumed time course of basic memory processes, such as encoding and retrieval. Finally, the basis of specific illusion-promotion and illusion-correcting mechanism in the different types of false memories should be explored, capitalizing on findings and procedures of recent studies in which tDCS of different brain regions has proven to modulate processes such as associative encoding (Gaynor & Chua, 2016), recollection accuracy (Gray, Brookshire, Casasanto, & Gallo, 2015), and memory monitoring (Chua & Ahmed, 2016).

To conclude, it is worth mentioning that our main finding is congruent with that from the only prior study that used tDCS to modulate activity in the left ATL (Boggio et al., 2009). Unlike this previous study, however, we manipulated polarity in order to better characterize the possible behavioral effect of tDCS. In line with the now well-demonstrated non-linear effects of tDCS (Fertonani & Miniussi, 2016; Jacobson, Koslowsky, & Lavidor, 2012), we showed that anodal tDCS enhanced performance at test (reduced false recognition in the case of associative lists) but cathodal tDCS did not lead to any behavioral impairment. Future studies combining non-invasive brain stimulation techniques and neuroimaging might help to clarify the neurocognitive mechanisms underlying the reduction of false memories that follows anodal tDCS of the left ATL. Data of this kind, together with computational modeling developments, will make substantial contributions to the field, especially to the understanding of the neural basis of the different types of semantic relatedness (Lambon Ralph et al., 2017). In the meantime, the new findings described here can be taken as an important step in corroborating and extending the conclusions from prior studies that, using different methodological approaches, have made substantial contributions to understanding the key role played by the ATL in semantic processing.

Author note

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Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.cortex.2017.05.004.

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