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Anterior temporal lobe mediates associative and taxonomic neighborhood effects in lexical processing ☆

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ABSTRACT

Processing a word's meaning activates some of its semantic neighbors that are related associatively or taxonomically. While prior studies have shown that both types of neighborhoods influence lexical processing, their underlying neural bases remain unclear, particularly regarding the involvement of the Anterior Temporal Lobe (ATL). This study used HD-tDCS to examine the role of the left lateral ATL in how associative and taxonomic semantic neighborhoods influence the lexico-semantic processing of abstract and concrete words. Participants ($N = 42$) performed a semantic concreteness judgment task on words, with and without left ATL stimulation, where neighborhood sizes were varied. A strong facilitative effect of concreteness was found in both real and sham conditions, consistent with the traditional concreteness effect. Both associative and taxonomic semantic neighborhoods influenced semantic judgments. Critically, ATL stimulation slowed responses to words with sparse neighborhoods, regardless of whether neighborhoods were defined associatively or taxonomically. Furthermore, the neighborhood effects were more readily apparent for abstract words, with significant interactions between stimulation and neighborhoods observed only in this subset. Together, the findings highlight the independent effects of associative and taxonomic neighborhoods in lexico-semantic processing and show that the ATL modulates the activation of both associative and taxonomic semantic neighborhoods, challenging models that characterize it solely as a taxonomic hub.

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1. Introduction

When people process the meaning of a word, they not only retrieve its specific semantic characteristics, but also activate the relevant semantic, orthographic, and phonological neighbors of the word (Buchanan et al., 2001; Carreiras et al., 1997; Grainger & Jacobs, 1996; Yates et al., 2004). Numerous studies have examined the effects of phonological and orthographic neighbors in various tasks involving lexical processing (Carreiras et al., 1997; Vitevitch & Luce, 2016; Ziegler et al., 2003). However, relatively few studies have explored the effect of semantic neighbors given its inherent complexity and richness, especially in abstract words (Reilly & Desai, 2017). Semantic neighborhood characteristics also affect lexical processing in multiple ways (Buchanan et al., 2001; Reilly & Desai, 2017).

Semantic neighborhoods can be characterized according to the types of semantic relationships linking a word to its neighbors. Two types are particularly relevant: associative and taxonomic relations. Associative relationships refer to the concepts that co-occur or interact in space and time (Lin & Murphy, 2001). For example, an associative neighbor of the word *dog* could be *bone,* as they co-occur in the same scenario or event (e.g., dogs chew on bones). The word co-occurrence patterns can also capture thematic relations that are tied to specific roles in events or schemas (Mirman et al., 2017; Whitmore et al., 2004). Taxonomic relationships, on the other hand, are based on the shared features and categorical similarities between concepts (McRae et al., 2005). For the word *dog*, a taxonomic neighbor would be *wolf* because dogs and wolves share common features such as four legs, tails, fur, and belong in the same category (canines). However, it remains unclear whether the two types of neighborhoods exert separable influences during lexico-semantic processing. The present study investigates how associative and taxonomic neighborhoods modulate the processing of abstract and concrete words using a semantic judgment task. This study used the term "association" broadly and thus subsumed thematic relations under the category of associative relations.

The semantic neighborhood of a word corresponds to the set of other words that are close to it within semantic space according to metrics such as associative strength, feature overlaps, and cosine similarity. Words that are more clustered are considered to have a denser neighborhood, and words that are more separated are considered to have a sparser neighborhood. Associative semantic neighborhoods are typically measured using association norms (De Deyne et al., 2019; Nelson et al., 1998). Taxonomic semantic neighborhoods are more difficult to measure because they typically rely on feature norms (McRae et al., 2005) that are manually generated and hence tend to be available for a relatively small number of concrete words. A third way to measure semantic neighborhoods is through corpus-based methods (e.g., LSA, Landauer & Dumais, 1997; HAL, Lund & Burgess, 1996; word2vec, Mikolov et al., 2013; GloVe, Pennington et al., 2014). Neighborhood estimations from common co-occurrence corpus-based methods contain a mix of both associative and taxonomic neighbors but tend to emphasize associative neighbors (Reilly & Desai, 2017). Prior studies of semantic neighborhoods have typically focused on associative neighborhoods (Riccardi et al., 2024; Schwartz et al., 2011; Schwen Blackett et al., 2022).

Semantic neighborhoods have been recognized as important predictors of lexical recognition and word naming (Buchanan et al., 2001; De Deyne et al., 2012; Muraki & Pexman, 2024). Early work in this field examined either associative or taxonomic neighborhoods exclusively, and they reported a facilitatory effect of semantic neighborhoods on word recognition (Buchanan et al., 2001; Pexman et al., 2002; Yates et al., 2003). For example, Buchanan et al. (2001) showed that words with denser associative neighborhoods were recognized faster and more accurately than those in sparse neighborhoods in lexical decision tasks. Mirman and Magnuson (2008) observed both facilitatory and inhibitory effects in processing taxonomic neighborhoods: word processing is slower when a word has many near neighbors (due to increased competition) and faster when a word has many distant neighbors (due to guided settling into the correct attractors). Furthermore, recent research found that the two types of semantic neighborhoods capture distinct aspects of semantic representations: associative neighborhoods capture contextual and experiential relationships, whereas taxonomic neighborhoods reflect hierarchical similarity (Mirman & Magnuson, 2008; Reilly & Desai, 2017). These observed representational differences indicate that associative and taxonomic semantic neighborhoods should be treated as separate measures in lexical processing (Mirman et al., 2017; Reilly & Desai, 2017).

When examining the effects of associative and taxonomic semantic neighborhoods, the literature reveals three prominent yet divergent aspects. The first aspect concerns the neural substrates supporting associative and taxonomic semantic relationships, particularly the involvement of the anterior temporal lobe (ATL). The Dual Hub model (Mirman et al., 2017) suggests a clear neuroanatomical distinction: ATL is primarily a taxonomic hub, whereas the temporoparietal junction (TPJ)/angular gyrus is a thematic hub. This account is supported by lesion-symptom mapping studies. Schwartz et al. (2011) demonstrated a dissociation between taxonomic and thematic errors in a picture naming task: individuals with post-stroke aphasia who produced taxonomic errors were more likely to have lesions in the left ATL, whereas those with thematic errors had lesions localized in the left TPJ. Furthermore, individuals with semantic dementia, characterized by temporal lobe atrophy, also showed impaired taxonomic knowledge but relatively preserved thematic knowledge in a lexical decision task (Merck et al., 2014) and a picture matching task (Merck et al., 2019). However, results from other studies challenged this disssociation. Jackson et al. (2015) showed that both associative and taxonomic relationships may engage the same neural network, including bilateral ATL, posterior temporal, and inferior frontal cortices. Moreover, studies of individuals with chronic aphasia reported that thematic relations are also processed in the ATL (Riccardi et al., 2024; Schwen Blackett et al., 2022), suggesting a role of ATL in processing both thematic and taxonomic relationships. Bonni et al. (2023) applied anodal tDCS to ATL and TPJ in healthy participants and found that while ATL stimulation influenced semantic processing primarily for taxonomic relations, TPJ stimulation did not affect judgments of thematic association. An fMRI study by Stochel and Sandberg (2025) also found no evidence in support of the dual hub model (Mirman et al., 2017; Schwartz et al., 2011) when both abstract and concrete words were included. In addition, 1 Hz rTMS stimulation of ATL slowed down the responses in semantic processing across different tasks for healthy participants (Hoffman & Crutch, 2016; Jung & Ralph, 2021; Pobric et al., 2007, 2010; Woollams et al., 2017). Taken together, these mixed results highlight the need for further investigation into the role of ATL in processing semantic neighborhoods. Notably, while the authors use the term "thematic," their description aligns closely with the broadly defined "associative" relationships in this paper.

A second aspect of mixed results centers on whether associative and taxonomic semantic neighborhood effects differ across concrete and abstract words (Recchia & Jones, 2012; Reilly & Desai, 2017). Empirical studies have reported contrasting patterns depending on neighborhood type and word concreteness: Reilly and Desai (2017) found that dense taxonomic neighborhoods slowed processing for concrete words but had no effects on abstract words, whereas Recchia and Jones (2012) reported that denser associative neighborhoods facilitated the processing of abstract words. These behavioral asymmetries can be explained by the Dual Coding Theory (DCT) (Paivio, 1991, 2010), which proposes that concrete words are represented by both linguistic and visual codes, while abstract words are mainly represented by linguistic codes. Under the DCT framework, the predominantly linguistic representation of abstract words may benefit from the contextual support of dense associative neighborhoods, whereas the sensory feature-based representation of concrete words may result in interference from feature overlaps and competition within dense taxonomic neighborhoods. Furthermore, independent evidence also indicates that abstract and concrete concepts engage partly dissociable neural systems (Bucur & Papagno, 2021; Desai et al., 2023; Johari et al., 2021, 2022; Sandberg et al., 2022; Skipper-Kallal et al., 2015; Wang et al., 2010), and are supported by distinct underlying semantic networks (Diveica et al., 2025a; Stochel & Sandberg, 2025). These mixed findings, together with the observed representational differences, raise the possibility that the effects of semantic neighborhoods may not generalize uniformly across word types. It therefore remains unclear whether the observed empirical differences (Recchia & Jones, 2012; Reilly & Desai, 2017) are attributable to neighborhood type (associative or taxonomic), word concreteness (concrete or abstract), or their interaction. In addition, when semantic knowledge was probed using associative rather than similarity-based relationships, a robust concreteness effect was observed in individuals with ATL degradation (Hoffman, Jones, & Ralph, 2013); however, this study did not include an abstract similarity condition. More broadly, prior research has rarely examined both associative and taxonomic neighborhoods within the same study and across concrete and abstract words, typically isolating a single neighborhood type or restricting analyses to a single word type. By including both neighborhood types and both word types, the present study addresses this gap and examines how ATL stimulations influence associative and taxonomic semantic neighborhood effects in lexico-semantic processing.

The third aspect of divergent findings concerns task-related differences in semantic neighborhood effects. The effects of semantic neighborhoods are highly task dependent (Danguecan & Buchanan, 2016). Implicit semantic tasks, such as lexical decision or picture naming, can often be performed with relatively shallow semantic activation based on surface-level lexical cues (e.g., prefixes or suffixes), whereas explicit semantic tasks require deliberate meaning evaluation and are therefore more likely to access deeper semantic representations. Prior work found that semantic neighborhood effects vary as a function of semantic processing depth. For example, some researchers (Pexman et al., 2008; Yap et al., 2011) reported that for concrete words, denser semantic neighborhoods, indexed by the number of features and number of associates, facilitated lexical decision performance but did not influence explicit semantic tasks. But Muraki and Pexman (2024) found that properties of a word's associative neighbors explained less variance in lexical decision performance than in semantic judgments. To directly test the role of semantic demand in neighborhood effects, Danguecan and Buchanan (2016) compared four tasks with varying semantic demands, and they found that associative neighborhood effects were consistently observed across four tasks only for abstract words, not for concrete words. Their finding aligns with the representation framework proposed by Crutch and Warrington (2005), who argued that concrete concepts have a categorical organization, whereas abstract words are represented in an associative neural network. Concrete words (e.g., *dog*) typically have low semantic diversity because their meanings remain relatively stable across most contexts. In contrast, abstract words (e.g., *power*) demonstrate high semantic diversity, making them more context-dependent and more subject to semantic demand (Hoffman, Lambon Ralph, & Rogers, 2013).

In summary, behavioral studies have shown that both associative and taxonomic neighborhoods affect lexical processing, interacting with word concreteness and task demand. The neuroanatomical bases of these relations are much less clear, with the role of ATL being especially controversial. Here, we use High-Definition transcranial Direct Current Stimulation (HD-tDCS) to investigate the role of ATL in the processing of associative and taxonomic neighborhoods in both concrete and abstract words in an explicit semantic judgment task. HD-tDCS, as a non-invasive brain stimulation technique, delivers a small electrical current through electrodes placed on the scalp with the goal of altering neuron depolarization susceptibility (Quartarone et al., 2006). Converging evidence indicates that instant excitatory and inhibitory effects have been observed with tDCS (e.g., Binney et al., 2018; Quartarone et al., 2006), demonstrating strong modulation of cognitive processes. HD-tDCS uses arrays of smaller, specially designed electrodes to improve the spatial resolution of stimulation. Brain modeling studies show that the cortical area modulated using the HD-tDCS configuration is more focal and more pronounced compared with the standard bipolar montage used in conventional tDCS (Mueller et al., 2022; Villamar et al., 2013). Furthermore, both anodal and cathodal HD-tDCS can modulate brain activity, although their effects are not necessarily equivalent to excitatory and inhibitory effects (Garnett et al., 2015). Several studies have reported reliable effects of anodal tDCS/HD-tDCS when targeting the ATL (e.g., Papagno et al., 2021; Ross et al., 2011). Effects from a single 20-minute session typically persist for up to 2 hours after stimulation (Kuo et al., 2013). In a direct comparison, anodal HD-tDCS produced more pronounced changes in EEG activity than cathodal stimulation (Tabari et al., 2024). Therefore, in the current study, we applied anodal HD-tDCS targeting the left lateral ATL for 20 min to test whether increasing cortical excitability would modulate lexico-semantic processing. The stimulated site includes both dorsolateral and ventrolateral aspects of the ATL, but not the medial surface due to HD-tDCS depth constraints. The lateral ATL regions support semantic processing across a range of concept types (Binney et al., 2016; Hoffman et al., 2015; Lambon Ralph et al., 2017), allowing us to clarify the ATL's role in semantic neighborhood processing.

In the present study, associative and taxonomic semantic neighborhoods were indexed using semantic neighborhood distance (SNDist). SNDist quantifies the average semantic distance between a target word and its semantic neighbors, with larger values indicating sparser semantic neighborhoods and smaller values indicating denser neighborhoods. Neighborhood membership can be defined using either a distance-based cut-off criterion or a fixed number of nearest neighbors (Buchanan et al., 2001). To capture different aspects of semantic neighborhoods, we included both associative and taxonomic SNDist measures, each validated in previous research (Reilly & Desai, 2017; Shaoul & Westbury, 2006).

The aim of the present study was to investigate the role of the left lateral ATL in processing abstract and concrete words with varying associative and taxonomic SNDists in an explicit semantic judgment task (i.e., concreteness judgment). While there are other options for explicit semantic tasks, such as living/nonliving judgments, many of them are not equally applicable to, or neutral with respect to, concrete and abstract words. The concreteness judgment task was chosen because it is equally applicable to both types of words. We hypothesized that both associative and taxonomic neighborhoods would independently influence the lexico-semantic processing of abstract and concrete words. Furthermore, we predicted significant interactions, where lateral ATL stimulation would modulate both associative and taxonomic neighborhood effects. Additionally, we anticipated that abstract and concrete words, due to their representational differences, would show differential neighborhood effects under the lateral ATL stimulation. This study contributes to the Special Issue (Diveica et al., 2025b) by using non-invasive brain stimulation to examine the neural basis of associative and taxonomic relationships in the semantic representations of words, and how task demands shape these effects. It highlights two dimensions of lexico-semantic representation pertaining to semantic neighborhoods and shows that they are an important source of variability in lexical concepts.

2. Methods

2.1. *Participants*

Forty-two healthy adults participated in the study (72% female, mean age = 20.4; SD = 1.9, age range = 18–25). We first excluded the participants whose average post-stimulation impedance exceeded 50 (N = 1), as well as those whose accuracy was more than two standard deviations below the group mean (N = 3), resulting in a total of 38 participants in the analysis. All participants were native English speakers, right-handed as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971), and had normal or corrected-to-normal vision and hearing. Participants reported no history of neurological, psychiatric, speech, or language disorders. Written consent was obtained from all participants, and they received monetary compensation or extra course credit for their participation. The study was approved by the Institutional Review Board of the University of South Carolina.

2.2. *Stimuli and procedure*

All participants completed two separate brain stimulation sessions: anodal and sham. During each session, they performed a semantic judgment task alongside five additional language tasks (not reported here). Because the order of these six tasks was counterbalanced, the onset of the semantic judgment task varied between 0 and 50 min after stimulation ended. The semantic judgment task required participants to use their right hand only to make a concreteness judgment. Participants first completed six practice trials to ensure that they understood the task and could adjust to the scalp sensations of HD-tDCS. During the task, participants were instructed to press "j" or "k" on a labeled keyboard to indicate whether the word was concrete or abstract for each trial as quickly as possible without making mistakes. A word was considered *concrete* if it referred to something that can be physically perceived or acted upon (e.g., *desk, house*), and *abstract* if it referred to something that cannot be physically perceived or acted upon (e.g., *love*, *determination*). The stimuli were presented in randomized order using E-Prime 2.0 (Psychology Software Tools). The order of stimulation conditions and key assignments were counterbalanced across participants. Their responses and reaction time for each trial were recorded. The task lasted approximately 6 minutes.

The stimuli included a total of 304 nouns with both associative and taxonomic semantic neighborhood distance (SNDist) measures available for each word. The associative SNDist was derived from the average distance between the target word and its closest associative semantic neighbors (e.g., *dog* and *bone*) that fell within its neighborhood membership threshold (Shaoul & Westbury, 2006), using the HAL model that emphasizes associative information. The membership threshold is calculated by randomly sampling millions of word pairs and computing the mean and standard deviation of their interword distance distribution. The neighborhood membership threshold is set at 1.5 SDs below the mean, corresponding to approximately the closest 6.7% of all word pairs. The taxonomic SNDist represents the average distance to a word's ten nearest semantic taxonomic neighbors (e.g., *dog* and *wolf*) (Reilly & Desai, 2017), derived from a 300-dimensional vector space explicitly designed to capture taxonomic relationships (Roller & Erk, 2016). Roller and Erk (2016) computed this semantic space using syntactic dependency context, demonstrating that the model effectively learned to identify hypernyms by capturing Hearst patterns (e.g., "animals such as dog"). For example, hypernyms (superordinate like "animal") and hyponyms (subordinate like "beagle") share identical syntactic slots, as they can both be the subject of "eats" or modified by the adjective "furry." By relying on these shared syntactic contexts, the model is thus encouraged to cluster hierarchical, taxonomic categories together (Erk, 2016; Reilly & Desai, 2017).

For both measures, larger values indicate sparser semantic neighborhoods, whereas smaller values indicate denser neighborhoods. The stimuli were further divided into two different stimulus sets based on Brysbaert, Warriner, and Kuperman's (2014) concreteness ratings: 152 concrete words (rating > 4.03, $M = 4.5$, SD = .3) and 152 abstract words (rating < 3.24, $M = 2.5$, SD = .5). The stimuli were divided into two subsets for use in two stimulation sessions per participant, so that there were no word repetitions across the stimulus sets, which avoids confounds from familiarity and repetition effects across sessions. The two sessions were separated by approximately four days (mean interval = 3.9, SD = 4.9, interval range = 1–27) to avoid potential stimulation carryover effects (Falcone et al., 2012; Zimerman et al., 2012).

In addition to concreteness, previous studies also found that several variables may contribute to lexical semantic processing: frequency (Brysbaert & New, 2009), valence (Warriner et al., 2013), arousal (Warriner et al., 2013), number of phonemes (Balota et al., 2007), and number of letters. We obtained all the relevant psycholinguistic properties of the words from the South Carolina Psycholinguistic Metabases (SCOPE) (Gao et al., 2023). To minimize potential confounding effects, we matched abstract and concrete words on associative SNDist, taxonomic SNDist, valence, arousal, number of phonemes, number of letters, and frequency (Table 1). Our taxonomic neighborhood estimates for over 100,000 words are available in SCOPE. Welch's two-sample *t*-tests confirmed that there are no significant differences for these variables (all $p > .1$).

Table 1 – Mean values (standard deviations) of lexical variables for abstract and concrete words. All differences were non- significant, all $p > .1$ (Welch's two-sample *t*-test).

	Abstract words	Concrete words	Welch's two-sample *t*-test
Associative SNDist	.56 (.07)	.57 (.06)	$p = .51$
Taxonomic SNDist	114.15 (53.70)	115.82 (48.32)	$p = .84$
Frequency	2.44 (.53)	2.50 (.45)	$p = .44$
Valence	5.34 (1.28)	5.06 (1.23)	$p = .18$
Arousal	4.33 (.91)	4.17 (.83)	$p = .24$
Number of phonemes	5.43 (1.61)	5.63 (1.47)	$p = .43$
Number of letters	6.50 (1.55)	6.62 (1.61)	$p = .64$

2.3. HD-tDCS configuration

Participants received both anodal and sham stimulations for 20 min using an MxN HD-tDCS Stimulator (Soterix Medical Inc., NY, USA). Electrode configurations and their corresponding current intensities for the left lateral ATL stimulation are presented in Table 2. HD-Explore and HD-Target software (Soterix Medical Inc., NY, USA) were used to compute electrode configurations and intensities. Both anodal and cathodal HD-tDCS can modulate brain activity, though they are not necessarily equivalent to excitatory and inhibitory effects (Garnett et al., 2015). Several studies reported robust effects of anodal tDCS/HD-tDCS when targeting the ATL (e.g., Papagno et al., 2021; Ross et al., 2011). In a direct comparison, anodal HD-tDCS produced more pronounced changes in EEG activity than cathodal stimulation (Tabari et al., 2024). Thus, we adopted anodal stimulation in this study. Fig. 1 shows the field intensity map and modeled current flow for anodal HD-tDCS targeting the left lateral ATL.

To administer HD-tDCS, a standard 10–20 EEG cap (EasyCap GmbH, Germany) was placed on the subject's head, with the Cz position midway between inion and nasion, and between the two mastoids. Anodal stimulation was used as real stimulation, and the control stimulation was a "passive sham" which involved a 60-second ramp-up at the beginning and a 60-second ramp-down at the end of the stimulation. This sham protocol mimicked the scalp sensation at the start and end of the session but ensured that no current was delivered throughout the stimulation.

We note that although anodal and cathodal tDCS stimulation are often labelled as excitatory and inhibitory, respectively, this terminology can be misleading especially for HD-tDCS (Garnett et al., 2015). The direction of effects depends on task demands (e.g., Berryhill et al., 2014; Framorando et al., 2021; Wang et al., 2021) and on the orientation of the neuron population relative to the current flow (e.g., Li et al., 2015; Rahman et al., 2013).

2.4. Analysis

The semantic judgment accuracy and reaction time (RT) of each participant for each trial were collected in the concreteness judgment task. We noted that abstract-concrete judgments can be subjective for words with intermediate

Table 2 – Electrode configurations in the left lateral ATL.

Location	Current
FT9	+1.00 mA
F9	−.60 mA
FP1	−.10 mA
C1	−.10 mA
PO9	−.20 mA

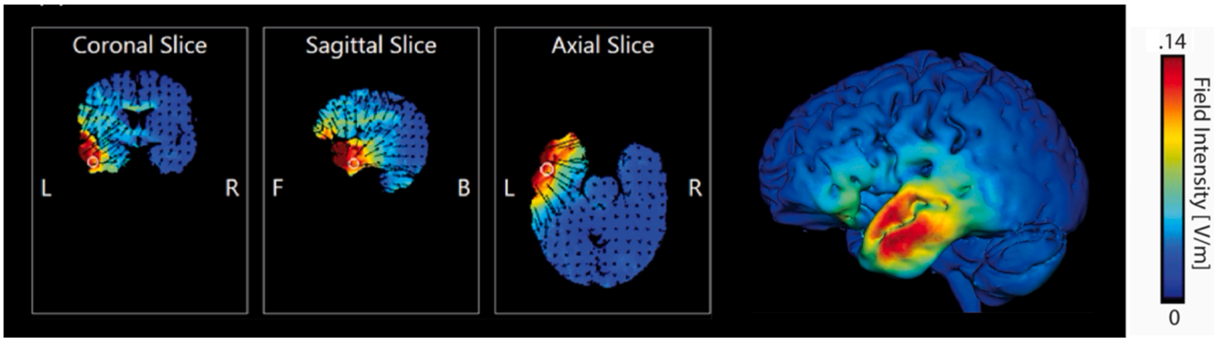

Fig. 1 – Field intensity map and current flow of the active stimulation.

ratings where there is no objectively wrong answer. To account for this, we split the concreteness ratings into three bins [1, 2.33], [2.34, 3.24], [4.03, 5]. These intervals were established by first dividing the Brysbaert, Warriner, and Kuperman's (2014) 1–5 rating scale into equal thirds, and then adjusting the resulting range to intersect with the actual cutoffs for our abstract (< 3.24) and concrete (> 4.03) stimuli. Items in the first and third bins represented clearly abstract and clearly concrete words, respectively, allowing for unambiguous accuracy evaluation. Items in the middle bin fell near the abstract-concrete boundary, for which either response was considered reasonable; therefore, responses to these items were not treated as incorrect, and their reaction times were retained for subsequent analyses. After calculating accuracy, we removed trials with incorrect judgments, RTs shorter than 300 ms or longer than 5,000 ms, and RTs that exceeded three standard deviations from each participant's mean, resulting in 92% valid trials.

Linear mixed-effects models were used to analyze RTs, with Subject included as a random intercept (Bates et al., 2015), using the *lmer* function in R (R Core Team, 2024). We investigated whether there were main effects of semantic variables (i.e., associative SNDist, taxonomic SNDist, concreteness, frequency, valence, arousal, number of phonemes, and number of letters) on the processing of the concrete and abstract words. To examine how a word's associative and taxonomic SNDists interacted with ATL stimulation, we tested the interactions between eachSNDists and stimulation, including other psycholinguistic variables as covariates.

3. Results

3.1. *Stimulation effects*

The overall mean RT (SD) for the task was 971 ms (371 ms). The mean RT (SD) in the sham condition was 947 ms (344 ms), and the mean RT (SD) in the real condition was 995 ms (396 ms). As shown in Fig. 2 and Table 3, compared to the baseline condition (i.e., sham), ATL stimulation significantly slowed down the semantic judgment RTs during lexico-semantic judgments ($B = 49.25$, $SE = 8.61$, $t = 5.72$, $p < .001$). When abstract and concrete words were analyzed separately, stimulation significantly slowed RTs in both abstract ($B = 43.44$, $SE = 12.13$, $t = 3.58$, $p < .001$) and concrete ($B = 54.24$, $SE = 11.97$, $t = 4.53$, $p < .001$) subsets compared to the sham condition. Furthermore, as shown in Fig. 2, a strong concreteness effect was also observed: concrete words were judged significantly faster than abstract words ($B = -16.74$, $SE = 4.14$, $t = -4.04$, $p < .001$). This effect of concreteness remained significant in both the real ($B = -15.22$, $SE = 6.00$, $t = -2.54$, $p = .011$) and sham ($B = -17.56$, $SE = 5.29$, $t = -3.32$, $p < .001$) subsets. In addition, post-hoc analyses revealed that there was no significant interaction between stimulation and concreteness ($B = 4.04$, $SE = 8.00$, $t = .51$, $p = .61$), suggesting that ATL stimulation affected abstract and concrete words similarly. All effects were obtained with covariates controlled, including associative SNDist, taxonomic SNDist, frequency, valence, arousal, number of phonemes, and number of letters.

3.2. *Associative and taxonomic SNDist effects*

We first investigated how two types of semantic neighborhood distance, associative SNDist and taxonomic SNDist, affected reaction times in the semantic judgment task for all words, collapsed across both sham and real conditions. As shown in Table 3, a linear mixed-effects regression model revealed main effects of semantic neighborhoods: both associative and taxonomic SNDists significantly independently influence lexico-semantic processing. Specifically, words with higher associative SNDist were processed faster than words with lower associative SNDist ($B = -182.78$, $SE = 82.13$, $t = -2.23$, $p = .026$), whereas words with higher taxonomic SNDist were processed slower than words lower taxonomic SNDist ($B = .23$, $SE = .10$, $t = 2.28$, $p = .022$). In addition to observed effects of stimulation, concreteness, and two SNDists, other psycholinguistic variables also significantly influenced the RTs of semantic judgment. A frequency effect was observed, with high-frequency words processed faster than low-frequency words ($B = -35.70$, $SE = 10.20$, $t = 3.50$, $p < .001$). An arousal effect showed that words with lower emotional intensity were processed more quickly than highly arousing words ($B = -14.32$, $SE = 5.33$, $t = -2.68$, $p = .007$). Similarly, a valence effect indicated that negative words were judged faster than positive words ($B = -10.65$, $SE = 3.65$, $t = -2.92$, $p = .004$). There was a marginal effect of the number of phonemes such that words with more phonemes were

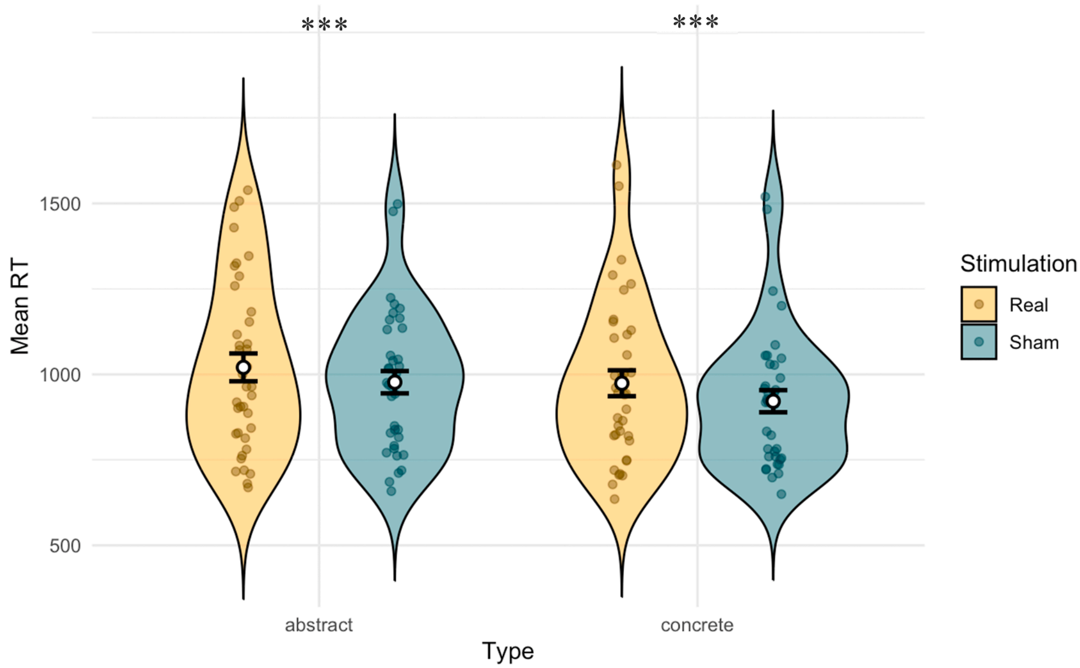

Fig. 2 – Reaction times (in millisecond) for semantic judgments of abstract and concrete words in real (yellow) and sham (turquoise) conditions. Violins represent the overall data distribution, colored dots denote individual subject means, and white circles indicate the condition means. Error bars represent 95% confidence intervals. *** $p < .001$.

Table 3 – Linear mixed-effects model results for reaction times of semantic judgments.

Fixed effects	B	SE	df	t	p	
(Intercept)	1318.43	61.53	468.67	21.42	<.001	***
Associative SNDist	−182.78	82.13	5280.08	−2.23	.026	*
Taxonomic SNDist	.23	.10	5280.06	2.29	.022	*
Frequency	−35.70	10.20	5280.07	−3.50	<.001	***
Concreteness	−16.74	4.14	5280.24	−4.04	<.001	***
Arousal	−14.32	5.33	5280.09	−2.68	.007	**
Valence	−10.65	3.65	5280.11	−2.92	.004	**
N_Phoneme	10.21	5.30	5280.09	1.92	.054	.
N_letter	−13.30	5.01	5280.11	−2.66	.008	**
Stimulation: Real	49.25	8.61	5280.24	5.72	<.001	***
Random effect	σ^2	SD				
Subject	38,764	196.9				
Residual	98,527	313.9				

Note. Model formula: *lmer* (RT ~ Associative SNDist + Taxonomic SNDist +
Frequency + Concreteness + Arousal + Valence + N_Phoneme +
N_letter + Stimulation + (1 | Subject)). *** $p < .001$, ** $p < .01$, * $p < .05$, . $p < .1$

judged more slowly ($B = 10.21$, $SE = 5.30$, $t = 1.92$, $p = .054$), as well as a significant effect of the number of letters such that words with more letters were processed faster ($B = -13.30$, $SE = 5.01$, $t = -2.66$, $p = .008$).

When the effects of associative and taxonomic semantic neighborhood effects were analyzed separately for the sham and real conditions, we found that without stimulation (turquoise lines in Fig. 3), words with higher associative SNDist values were processed significantly faster than those with lower associative SNDist values ($B = -479.55$, $SE = 101.01$, $t = -4.75$, $p < .001$), and this effect was independent of taxonomic neighborhood effect. However, taxonomic SNDist did not significantly predict RTs in the sham condition ($B = .06$, $SE = .13$, $t = .51$, $p = .61$) when controlling for the effects of associative SNDist. In the real stimulation condition (yellow lines in Fig. 3), both associative and taxonomic SNDist effects were marginal: words with higher associative SNDist values tends to be processed faster than those with lower associative SNDist ($B = -197.99$, $SE = 113.30$, $t = -1.75$, $p = .08$), while words with higher taxonomic SNDist values were processed more slowly than those with lower values ($B = .24$, $SE = .14$, $t = 1.72$, $p = .09$).

To investigate the main question of the role of ATL in semantic neighborhood effects, we examined the interaction between stimulation and both types of SNDists. As shown in Fig. 3, after regressing out the effects of other psycholinguistic variables, there was a significant interaction between stimulation and associative SNDist, indicating that compared to the sham condition, ATL stimulation increased the RTs for words with higher associative SNDist ($B = 338.32$, $SE = 135.81$, $t = 2.49$, $p = .01$). A significant interaction was also found between stimulation and taxonomic SNDist, showing that compared to the sham condition, ATL stimulation similarly increased the RTs for words with higher taxonomic SNDist ($B = .37$, $SE = .17$, $t = 2.16$, $p = .03$). We adopted leave-one-subject-out analyses and found that the interaction between stimulation and associative SNDist remained significant in 100% of iterations (mean $b = 338.28$, $SD = 18.57$, range:

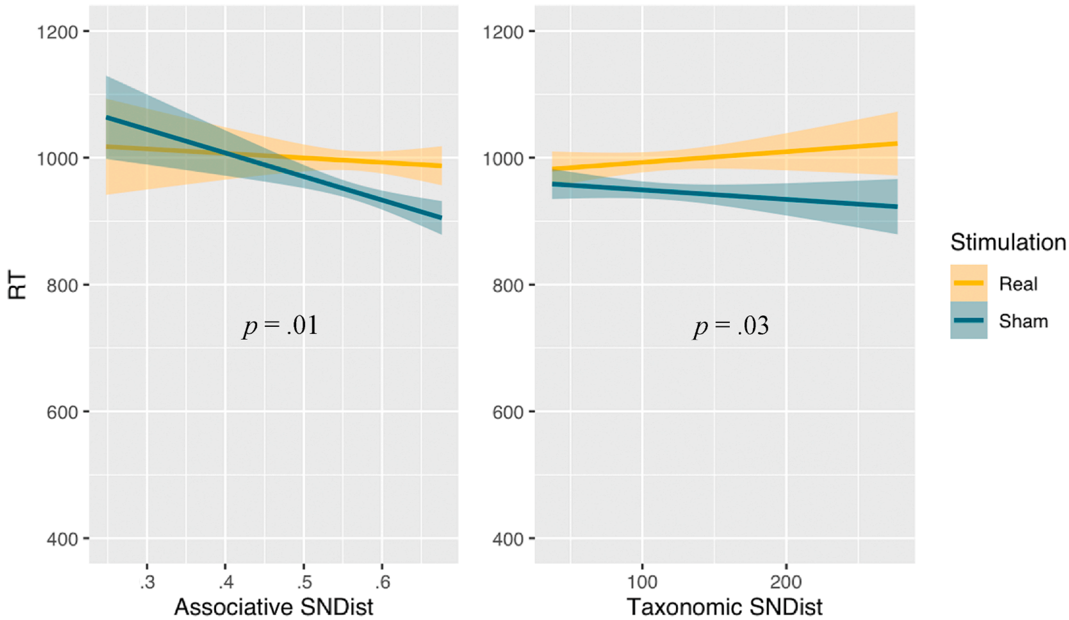

Fig. 3 – The effect of associative SNDist (left) and taxonomic SNDist (right) on reaction times in real (yellow) and sham (turquoise) conditions. The shaded areas represent standard error. *p* values indicate the significance of the interaction between SNDist and stimulation. High SNDist values reflect large semantic distance, indicating sparse semantic neighborhoods. Low SNDist values reflect small semantic distance, indicating dense semantic neighborhoods.

283.31–373.42), and the interaction between Stimulation and taxonomic SNDist remained significant in 89.5% of iterations (mean $b = .37$, SD = .03, range: .31–.42), with no sign reversals observed across iterations in either models, attesting to the robustness of results. In addition, post-hoc Wald tests confirmed that the slopes of associative SNDist and taxonomic SNDist effects were significantly different in the sham condition ($\chi^2 = 11.53$, $p < .001$), but not in the real condition ($\chi^2 = .36$, $p = .55$).

3.3. Semantic neighborhood effects in concrete and abstract words

We next examined whether the interactions between the two types of SNDist and ATL stimulation differed between concrete and abstract words. For abstract words, compared to the sham condition, ATL stimulation showed a marginal interaction with associative SNDist ($B = 332.76$, $SE = 185.65$, $t = 1.80$, $p = .07$), whereas no significant interaction was found for concrete words ($B = 304.90$, $SE = 202.74$, $t = 1.50$, $p = .13$) (Fig. 4). Similarly, a significant interaction between ATL stimulation and taxonomic SNDist was also observed for abstract words ($B = .53$, $SE = .23$, $t = 2.31$, $p = .02$), but not for concrete words ($B = .16$, $SE = .25$, $t = .62$, $p = .54$) (Fig. 5). These results suggest that the modulation of ATL stimulation on semantic neighborhood effects is more readily apparent for abstract words.

To further explore how word concreteness influences semantic neighborhood effects, we tested whether the effects of SNDist interacted with concreteness ratings in the real and sham conditions separately. In the real stimulation condition, there was a marginal interaction between concreteness and taxonomic SNDist: the inhibitory effect of taxonomic SNDist on RTs (i.e., slower processing for words with higher taxonomic SNDist values) diminished as words became more concrete ($B = -.24$, $SE = .13$, $t = -1.84$, $p = .07$). No significant interaction was found between concreteness and associative SNDist. In the sham condition, neither type of SNDist showed a significant interaction with concreteness.

4. Discussion

We examined the effects of associative and taxonomic neighborhoods in concrete and abstract words during a semantic judgment task, using HD-tDCS targeting the left lateral ATL. Consistent with our hypothesis, we found that both associative and taxonomic neighborhoods independently influence lexico-semantic processing. Moreover, we confirmed the hypothesis that lateral ATL stimulation would modulate both associative and taxonomic neighborhood effects in lexico-semantic processing. As predicted, we also observed differential neighborhood effects between abstract and concrete words under the ATL stimulation. The results are discussed below.

First, in the absence of lateral ATL stimulation, we observed a strong facilitative effect of concreteness on semantic processing: participants judged concrete words faster than abstract words, even after controlling for other psycholinguistic variables. This result aligns with findings from previous studies relating to the concreteness effect (Danguecan & Buchanan, 2016; Hoffman et al., 2015; Paivio,

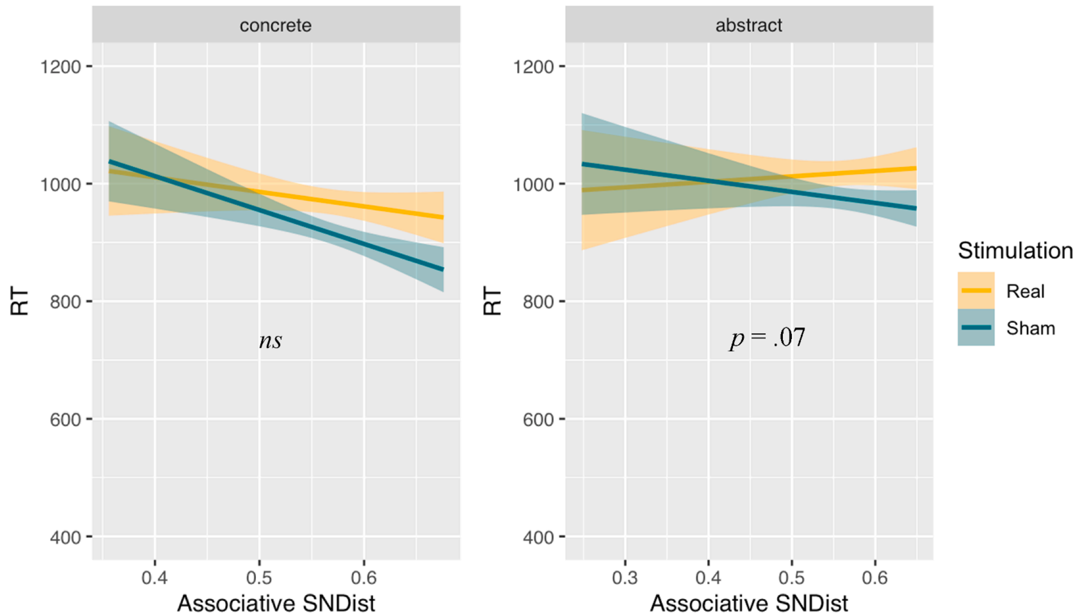

Fig. 4 – The effect of associative SNDist on reaction times in real (yellow) and sham (turquoise) conditions in concrete (left) and abstract (right) subsets. The shaded areas represent standard error. *p* values indicate the significance of the interaction between associative SNDist and stimulation.

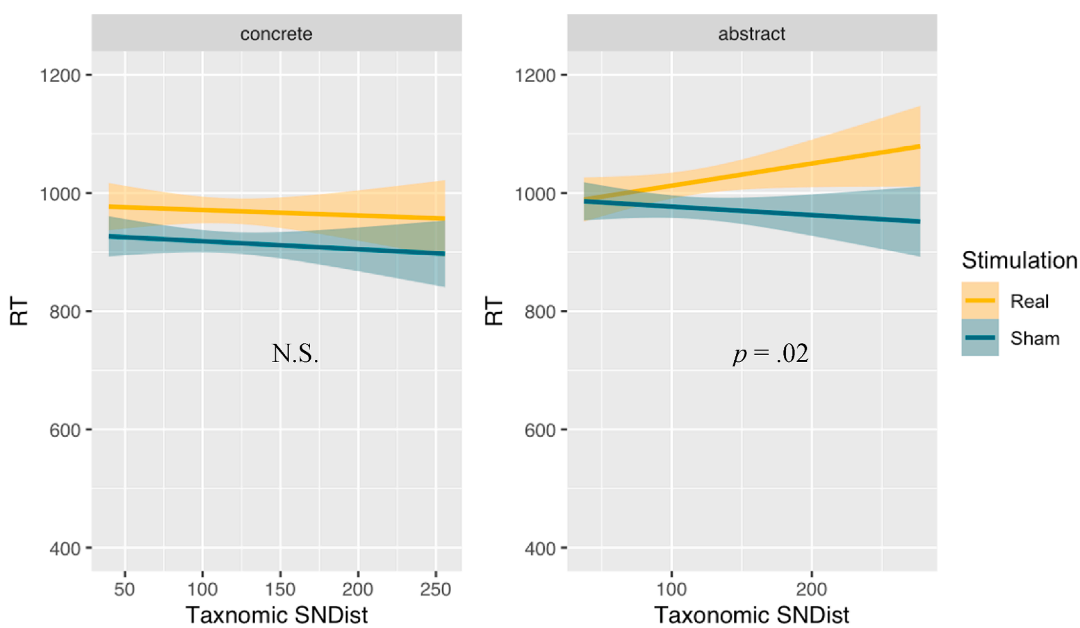

Fig. 5 – The effect of taxonomic SNDist on reaction times in real (yellow) and sham (turquoise) conditions in concrete (left) and abstract (right) subsets. The shaded areas represent standard error. *p* values indicate the significance of the interaction between taxonomic SNDist and stimulation.

2010; Reilly & Desai, 2017). Moreover, the effects of associative and taxonomic neighborhoods were significantly different in the sham condition, supporting the proposal that these two types of semantic neighborhoods engage separate cognitive and neural mechanisms (Mirman et al., 2017; Reilly & Desai, 2017; Schwartz et al., 2011; Zhang et al., 2023). Furthermore, we found that, in the absence of ATL stimulation, words with more distant associative neighbors were processed more quickly than those with more close associative neighbors, aligning with the findings from Mirman and Magnuson (2008). However, this finding contrasts with previous studies using lexical decision tasks, which reported a facilitative effect of dense associative semantic neighborhoods (Buchanan et al., 2001; Pexman et al., 2002; Yates et al., 2003). Two factors may account for this discrepancy. First, prior studies often did not control for the potential influence of taxonomic neighborhood effects, whereas our study accounted for this by regressing out their confounding influence. Second, the difference likely stems from the nature of the task. Lexical decision tasks may benefit from spreading activation to closely related words, because the task is only to verify that the stimulus is a word, but not necessarily to distinguish it from other words. In contrast, semantic judgment tasks—such as judging whether a word is concrete or abstract—require selecting or evaluating specific semantic features of the target word. In this context, the automatic activation of a word's dense associative neighborhood can create response competition during decision-making (Pexman, 2012). Because a word's associative neighbors may differ on the specific semantic feature being evaluated, their automatic activation can introduce task-irrelevant features that need to be suppressed before making an accurate semantic judgment (Muraki & Pexman, 2024).

Our results also show that the lateral ATL plays a causal role in activating both associative and taxonomic neighborhoods, providing more focal evidence for the involvement of the ATL in lexico-semantic processing. First, lateral ATL stimulation significantly slowed lexical semantic processing, corroborating the inhibitory effects reported in both tDCS (Bonni et al., 2023) and rTMS literature (Hoffman & Crutch, 2016; Jung & Ralph, 2021; Pobric et al., 2007, 2010; Woollams et al., 2017). Moreover, this stimulation effect remained significant for both abstract and concrete subsets, suggesting that the lateral ATL plays a role in the semantic processing of both abstract and concrete words. This finding was partially consistent with Hoffman et al. (2015) who reported ATL activation for both abstract and concrete words. Importantly, we observed significant interactions between ATL stimulation and both types of semantic neighborhoods. Specifically, ATL stimulation increased reaction times for words with sparse neighborhoods, whether defined associatively or taxonomically. This finding is consistent with recent evidence from picture naming studies, which reported increased associative and taxonomic naming errors with ATL disruption (Riccardi et al., 2024; Schwen Blackett et al., 2022; Zhang et al., 2023). Although these prior studies focused on picture naming, the convergence across tasks highlights the role of the ATL in lexical access. However, this is inconsistent with the Dual Hub account, which proposes that the ATL is a taxonomic hub, while the temporo-parietal junction is an associative hub (Mirman et al., 2017; Schwartz et al., 2011). Apart from the difference in tasks, the current study differs from prior picture naming studies in another important way, in that half of our stimuli were abstract words. Picture naming tasks, such as those used in Schwartz et al. (2011), are restricted to concrete items. Taken together, our findings provide evidence that lateral ATL contributes to both associative and taxonomic semantic neighborhood processing of words across the concreteness spectrum, challenging the view that it serves exclusively as a taxonomic hub.

What are the possible roles of lateral ATL with respect to semantic neighborhoods? One possibility is that the ATL acts as a semantic hub representing integrated concepts and their broader networks (Lambon Ralph et al., 2010, 2017; Patterson et al., 2007). Evidence from semantic dementia shows that atrophy centered around ATL degrades fine-grained conceptual distinctions, with words in sparse neighborhoods being especially vulnerable (Patterson et al., 2007). Furthermore, converging evidence from decoding studies using EEG (Farahibozorg et al., 2022), MEG (e.g., Mollo et al., 2017), EcoG (e.g., Frisby et al., 2026), rTMS (e.g., Jung & Ralph, 2021), and fMRI (e.g., Frisby et al., 2025; Hoffman et al., 2015), corroborates that the ATL plays an important role in lexico-semantic processing. In the present study, we found that disrupting ATL *via* HD-tDCS impaired processing of words in sparse neighborhoods, which is consistent with the semantic hub account.

This is not the only explanation of these effects, however. An alternative possibility is that the effects are at the *lexical* level rather than at the semantic level. For example, in the interactive two-step model (Dell et al., 2007; Dell & O'Seaghdha, 1992; Schwartz et al., 2006), an intermediate "word" level (similar in some respects to the lemma level in other models) represents units that provide a mapping between semantics and phonology, but are not semantic or phonological themselves. Stimulation of lateral ATL may therefore perturb this intermediate level at which semantic and phonological information interact in lexical processing. For words in a sparse semantic neighborhood, fewer overlapping features or associates may increase reliance on the integrative, top-down lexico-semantic processing. When this lexico-semantic process is disrupted by lateral ATL stimulation, access to semantic representations becomes less efficient, resulting in slowed reaction times. The current study was not designed to distinguish between these alternatives, and hence this possibility is suggested as a speculation. We leave this as an open question that requires further investigation.

Finally, we found that abstract and concrete words differ with respect to the effect of lateral ATL stimulation. Overall, we observed that ATL stimulation slowed responses for words with sparse semantic neighborhoods regardless of neighborhood type, and the interactions between stimulation and semantic neighborhoods were found for abstract words. Prior studies have indicated a role for dorsolateral ATL in processing abstract words (e.g., Hoffman et al., 2015), though the HD-tDCS spatial resolution does not allow us to distinguish between contributions of dorsal versus ventral ATL here. Regarding the specific neighborhood effects, we found that ATL stimulation showed a marginal interaction with associative SNDist, consistent with prior behavioral studies showing that abstract words rely more heavily on associative relationships (Danguecan & Buchanan, 2016; Recchia & Jones, 2012). Based on a case study of an aphasic individual, Crutch and Warrington (2005) argued that abstract but not concrete words are represented in an associative network, because they showed effects of semantic refractory access in multiple experiments where associations were modulated. This suggested that abstract and concrete words are based on qualitatively different representational systems, consistent with the current results.

Regarding taxonomic neighborhoods, our results differed from Reilly and Desai (2017): we observed taxonomic neighborhood effects for abstract words, while Reilly and Desai (2017) found that taxonomic semantic neighborhood effects were more prominent for concrete words. This discrepancy can again be explained by the difference in tasks: Reilly and Desai (2017) employed a lexical decision task with implicit semantic processing, whereas the present study used a semantic decision task in which semantic processing was more explicit. The absence of significant interaction (between ATL stimulation and taxonomic neighborhood effect) in concrete words may be more consistent with the lexical account as outlined above. Concreteness may modulate reliance on taxonomic structure in the following way. Concrete objects exhibit a feature-based similarity structure. For example, animals have many shared features (due to their evolutionary origin), and tools have similar overlapping features (because they are designed for specific functions). Abstract concepts are not subject to similar physical constraints and do not exhibit an obvious similar feature-based taxonomic structure. Because the ATL is proposed to integrate these distributed features, disruption of the ATL may be expected to modulate taxonomic neighborhood effects more for concrete words. However, this pattern was not observed. Instead, the significant interaction between ATL stimulation and taxonomic neighborhood effect was found for the abstract subset, suggesting that the ATL may be more likely involved in integrating semantic and phonological information during lexical processing. Consistent with this, we also found a marginal interaction showing that the inhibitory effect of dense taxonomic neighborhoods diminished as word concreteness increased in the real stimulation subset. Hence, with the caveat that the power to examine these subsets separately was limited due to the halving of the stimulus set, and the marginal findings should be interpreted with caution, these results are also consistent with a lexical role of the ATL.

Some limitations of the study are as follows. First, separating the stimulus set by concreteness or by stimulation type effectively halved the number of stimuli, which reduced statistical power, potentially resulting in some marginal findings. Future studies should consider increasing the stimulus set to further clarify these effects. We also note the potential variability in the strength of the stimulation resulting from the fact that the task was administered between 0 and 50 minutes after the end of stimulation (with a mean of approximately 25 minutes). While some modulation in the strength of stimulation is possible during this window, significant stimulation effects are expected throughout this window, as significant effects are reported at least till 2 hours and are eliminated around only 6 hours (Kuo et al., 2013). All participants were stimulated well within this window. Finally, stimulation with HD-tDCS was limited mainly to the lateral half of ATL. The ventromedial surface of ATL is especially thought to be relevant for concrete concepts (Binney et al., 2016; Hoffman et al., 2015), which was not stimulated here. Thus, the role of the lateral–medial axis in processing semantic neighborhoods with respect to concrete versus abstract words awaits further investigation.

5. Conclusions

The results demonstrate distinct effects of associative and taxonomic semantic neighborhoods in lexical semantic processing, with lateral ATL stimulation influencing the processing of both types of semantic relationships. These findings indicate that lateral ATL supports the activation of associative and taxonomic semantic neighborhoods in lexico-semantic processing. Notably, ATL stimulation slowed responses to words with sparse semantic neighborhoods regardless of whether neighborhoods were defined associatively or taxonomically, raising questions about the accounts that characterize the ATL primarily as a taxonomic hub. In addition, the effects of lateral ATL stimulation on semantic neighborhood activation were more readily apparent for abstract words, contributing to the ongoing dialogue on how abstract and concrete words are differently structured and processed in the brain.

Scientific transparency statement

DATA: All raw and processed data supporting this research are publicly available: https://osf.io/3qh68/files/drzsk, https://osf.io/3qh68/files/v6sc8.

CODE: All analysis code supporting this research is publicly available: https://osf.io/3qh68/files/d8r9j.

MATERIALS: All study materials supporting this research are publicly available: https://osf.io/3qh68/files/n3z5t; https://osf.io/3qh68/files/t43ec; https://osf.io/3qh68/files/q6h98.

DESIGN: This article reports, for all studies, how the author(s) determined all sample sizes, all data exclusions, all data inclusion and exclusion criteria, and whether inclusion and exclusion criteria were established prior to data analysis.

PRE-REGISTRATION: No part of the study procedures was pre-registered in a time-stamped, institutional registry prior to the research being conducted. No part of the analysis plans was pre-registered in a time-stamped, institutional registry prior to the research being conducted.

For full details, see the *Scientific Transparency Report* in the supplementary data to the online version of this article.

Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cortex.2026.06.026.

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