ORIGINAL ARTICLE

Taxonomic and thematic semantic relationships in picture naming as revealed by Laplacian-transformed event-related potentials

Elizabeth J. Anderson[1,2] | Katherine J. Midgley[3] | Phillip J. Holcomb[3] | Stephanie K. Riès[4]

[1]Joint Doctoral Program in Language and Communicative Disorders, San Diego State University, San Diego, California, USA

[2]Joint Doctoral Program in Language and Communicative Disorders, University of California San Diego, La Jolla, California, USA

[3]Department of Psychology, San Diego State University, San Diego, California, USA

[4]School of Speech, Language, and Hearing Sciences, San Diego State University, San Diego, California, USA

Correspondence
Elizabeth J. Anderson, Laboratory for the Brain Dynamics of Language, SDSU Research Foundation, 6495 Alvarado Rd., Suite 103, San Diego, CA 92120, USA.
Email: eanderson9977@sdsu.edu

Abstract

Semantically related concepts co-activate when we speak. Prior research reported both behavioral interference and facilitation due to co-activation during picture naming. Different word relationships may account for some of this discrepancy. Taxonomically related words (e.g., *WOLF-DOG*) have been associated with semantic interference; thematically related words (e.g., *BONE-DOG*) have been associated with facilitation. Although these different semantic relationships have been associated with opposite behavioral outcomes, electrophysiological studies have found inconsistent effects on event-related potentials. We conducted a picture-word interference electroencephalography experiment to examine word retrieval dynamics in these different semantic relationships. Importantly, we used traditional monopolar analysis as well as Laplacian transformation allowing us to examine spatially deblurred event-related components. Both analyses revealed greater negativity (150–250 ms) for unrelated than related taxonomic pairs, though more restricted in space for thematic pairs. Critically, Laplacian analyses revealed a larger negative-going component in the 300 to 500 ms time window in taxonomically related versus unrelated pairs which were restricted to a left frontal recording site. In parallel, an opposite effect was found in the same time window but localized to a left parietal site. Finding these opposite effects in the same time window was feasible thanks to the use of the Laplacian transformation and suggests that frontal control processes are concurrently engaged with cascading effects of the spread of activation through semantically related representations.

KEYWORDS
ERPs, language production, Laplacian transformation, semantics

1 | INTRODUCTION

Speech production is a key facet of daily communication, and speakers are typically able to select the correct words to convey their thoughts with ease. Despite the ease with which we speak, identifying the neural processes underlying speech production is a complex task. Several models have been proposed to describe the cognitive processes occurring during language production (Dell et al., 2013; Indefrey & Levelt, 2004; Rabovsky et al., 2016). Such models consistently feature recognized stages of processing such as phonological, morphological, and semantic stages, and all agree upon the idea that semantically related words are co-activated when we produce language. Semantic co-activation refers to the fact that during word retrieval, the target word will receive activation as will its semantic neighbors. The speaker is then tasked with selecting the correct word from the activated options. However, how and when representations are activated at each of the stages and how activation at one stage impacts activation at another stage remains unclear. Here, we address the impact of semantic co-activation during language production by using two complementary electroencephalography (EEG) analysis methods to study the retrieval of unrelated and related nouns.

1.1 | Thematic versus taxonomic semantic relationships

Although the existence of semantic co-activation is largely undisputed, the effect of this co-activation on language production and associated brain dynamics currently remains under examination. Evidence exists to support both semantic interference and facilitation on behavior following semantic co-activation (Alario et al., 2000; Bloem et al., 2004; Costa et al., 2005). Semantic interference corresponds to an increase in naming latencies and error rates, whereas semantic facilitation corresponds to a decrease in naming latencies and error rates as the result of the increased activation of semantically related words. These opposing effects of semantic interference and facilitation can be observed in the context of taxonomically related versus thematically related stimuli, respectively (e.g., Alario et al., 2000; Costa et al., 2005; de Zubicaray et al., 2013). Taxonomically related words belong to the same semantic category and have shared features, such as *BEE* and *WASP*. Thematically related words occur together in events or scenarios, such as *BEE* and *HONEY*. This dissociation between semantic interference in taxonomically related stimuli versus facilitation in thematically related stimuli has been observed in Picture-Word Interference (PWI) tasks where participants name pictures

with overlapping to be-ignored semantically related distractor words (Abdel Rahman & Melinger, 2007; Alario et al., 2000; Costa et al., 2005; de Zubicaray et al., 2013; La Heij et al., 1990; Sailor et al., 2009), and more recently in the blocked cyclic picture naming paradigm where participants name pictures in blocks of related or unrelated pictures which are repeated for several cycles (McDonagh et al., 2020; although see Roelofs, 2018 and Rose & Abdel Rahman, 2016 for reports of similar interference effects across the different types of semantic relationships in blocked-cyclic and continuous naming tasks). Several explanations have been proposed to account for these opposing effects.

There is a consensus that semantic facilitation is the result of spreading activation from semantic representations (e.g., insect, flying.) to lexical representations that share these semantic attributes (e.g., *bee*, *wasp*.) and to frequently co-activated representations (e.g., honey for *bee*) (Alario et al., 2000; Bloem et al., 2004; Costa et al., 2005). However, there are different explanations concerning the origins of interference, including increased competition at the level of lexical selection (e.g., Damian et al., 2001; Howard et al., 2006; Roelofs & Piai, 2013), incremental changes in connection weights between semantic and lexical representations (e.g., Harvey et al., 2019; Mahon et al., 2012; Mahon & Navarrete, 2014; Oppenheim et al., 2010), and conflict at the level of response preparation (e.g., Blackford et al., 2012; Caramazza & Costa, 2000; Costa et al., 2005; Giezen & Emmorey, 2016; Mahon et al., 2007).

These theories were formulated with evidence compiled from several picture naming paradigms, primarily including the blocked-cyclic, continuous naming, and PWI tasks. Blocked-cyclic (Damian et al., 2001; Oppenheim et al., 2010) and continuous naming (Harvey et al., 2019; Howard et al., 2006) tasks have both been used as evidence to support the idea that semantic interference originates in links between concepts and lexical items and manifests at the stage of lexical selection (Belke & Stielow, 2013; Howard et al., 2006; Oppenheim et al., 2010; Roelofs, 2018). There is debate surrounding the locus of the semantic interference effect in the PWI task. For example, the response exclusion hypothesis (Mahon et al., 2007) theorizes that semantic interference originates from late post-selection monitoring processes during articulation in response to the structure of the task rather than lexical retrieval processes (Blackford et al., 2012; Caramazza & Costa, 2000; Costa et al., 2005; Giezen & Emmorey, 2016; Mahon et al., 2007; Navarrete et al., 2014). Alternatively, a comparison of the three paradigms from Roelofs (2018) suggests that all three tasks are examining word retrieval with semantic interference occurring at the stage of lexical selection.

Roelofs cites overlapping times windows of semantic effects in electrophysiological studies (Aristei et al., 2011; Blackford et al., 2012; Costa et al., 2009; Dell'Acqua et al., 2010; Janssen et al., 2015; Maess et al., 2002; Piai et al., 2014; Rose & Abdel Rahman, 2016) and similar increases in semantic error rates in individuals with left MTG lesions across paradigms (Harvey & Schnur, 2015; Piai & Knight, 2018; Schwartz et al., 2009) to support this claim.

Although all of these proposed theories are in agreement that interference emerges after or concurrently with initial lexical activation, what remains unclear is the relative timing of these processes and possible co-occurrence of facilitation and interference effects. The current study investigates the relative timing and potential co-occurrence of facilitation and interference effects by using both traditional ERP analysis as well as Laplacian transformation providing an estimate of the current source density to examine how different semantic relationships affect the spatio-temporal dynamics of word retrieval during word production.

1.2 | Electrophysiology of language production

Electrophysiological studies provide evidence on the timing of processes required to produce single words that cannot be understood from behavioral data alone. The manipulation of semantic context has been used as a means to probe when brain activity is associated with different processes leading to word production. Several ERP components have been found to be sensitive to semantic context in PWI tasks, including the N1 (Hirschfeld et al., 2008; Wamain et al., 2015), P3 (Wamain et al., 2015), and N400 components (Blackford et al., 2012; Kutas & Federmeier, 2011). In particular, ERP studies of word production have generally converged on two time windows associated with semantic context effects. The first window being between 150 and 250 ms after stimulus onset and associated with visual processing and lexical access based on the observation of semantic context effects in this early time window (Aristei et al., 2011; Blackford et al., 2012; Costa et al., 2009; De Cesarei et al., 2013; Eddy et al., 2006; Eddy & Holcomb, 2010; Strijkers et al., 2010). The second window being centered on the N400, between 300 and 500 ms poststimulus onset, as this established component in language research has been shown to be sensitive to lexico-semantic processing (Kutas & Federmeier, 2011; Kutas & Hillyard, 1980) and to semantic context in the direction of semantic facilitation (larger N400 in unrelated vs. related blocks). In line with facilitatory effects

found on behavioral measures, thematic relationships have been consistently associated with facilitation effects on ERPs in PWI studies (i.e., smaller amplitudes for semantically related than unrelated stims in all of the aforementioned time windows; Hirschfeld et al., 2008; Wamain et al., 2015). However, results have been less consistent for taxonomic relationships. Whereas some of these studies have reported no difference in amplitude between related and unrelated conditions (Hirschfeld et al., 2008; Wamain et al., 2015), other studies have reported reduced N400 in related versus unrelated conditions for taxonomic pairs (Blackford et al., 2012; Roelofs et al., 2016; see Kutas & Federmeier, 2011). Possible reasons for these inconsistencies include inconsistent study designs, individual differences in semantic knowledge and access, ambiguous interpretations of findings, and the types of ERP analysis techniques used.

In particular, concerning study design, previous studies have not always analyzed taxonomic and thematic relationships against a baseline unrelated condition in order to independently and systematically compare the neurological and behavioral effects of each relationship (e.g., Aristei et al., 2011). Only two of the above-mentioned studies explicitly discussed controlling for the degree of relatedness between pairs in each condition (Blackford et al., 2012 with pairwise comparison values and Wamain et al., 2015 with surveys). In addition, while several electroencephalographic studies have examined the impact of semantic relatedness on the brain dynamics underlying picture naming, few of these studies have directly compared different types of semantic relatedness using EEG (Aristei et al., 2011; Hirschfeld et al., 2008; Wamain et al., 2015). In order to optimize the comparison of semantic context effects between taxonomic and thematic conditions, it is important to directly compare these conditions to ensure that the results are not due to confounding factors such as differences in relatedness strength between conditions. Indeed, the variable ERP effects observed across taxonomic and thematic relationships could be linked to individual differences in similarity judgments between taxonomic and thematic relationships. Taxonomic and thematic similarity judgment has been shown to predict ERP amplitude during passive word reading (Honke et al., 2020). In the current study we controlled for group level differences in stimulus perception prior to the onset of the study through a norming survey to ensure matched ratings of relatedness across conditions and corpus linguistics analysis (see Section 3.2).

Concerning result interpretation, using difference waves has led to debatable interpretations of taxonomic semantic context effects. In particular, using a blocked cyclic naming task with taxonomically related and unrelated items, Janssen et al. (2015) claimed to report both

an early facilitation (300–400 ms) and later interference effect (500–750 ms) in their ERP data. However, for both the early and late effects the waveforms were larger for unrelated than related condition, except that the early effect was found on a negative-going waveform and the late effect was found on a positive-going waveform. Therefore, analyzing difference waves led to incorrectly interpreting these effects as being opposite. In order to avoid this issue in the present study, we will focus on analyzing waveforms in the individual conditions rather than solely focusing on the difference waves.

A fourth possible reason for the inconsistent ERP findings may be linked to the type of ERP analysis techniques used. Interestingly, previous studies have found that the effects seen on electrophysiological components are not always in the same direction as the effects found on behavioral results. Indeed, the blocked picture naming and the PWI paradigms using taxonomically related stimuli typically elicit semantic interference on behavior, but opposite effects have often been found on associated ERP components. Blackford et al. (2012) used the PWI paradigm and demonstrated varying dissociations between behavior and ERPs based on the characteristics of presented stimuli. In particular, the semantically related condition, in which the picture was primed by a taxonomically related word, led to semantic interference but electrophysiological priming (i.e., decreased amplitude in the related compared to unrelated condition). This suggests that semantic priming may be taking place in the brain even if semantic interference is the outcome on behavioral measures. However, ERP effects associated with semantic interference have been harder to find across language production paradigms (Blackford et al., 2012; Hirschfeld et al., 2008; Wamain et al., 2015; for a review see Nozari & Pinet, 2020). A possibility for the absence of this effect may be linked to several reasons including the analysis techniques used. Previous studies using scalp EEG have mainly focused on monopolar types of analyses, where the signal at each electrode is compared to one predefined reference electrode and where spatial resolution is typically relatively low. This traditional approach to visualizing ERPs might have led to missing more focal effects, resulting in an incomplete description of the brain mechanisms engaged in processing different kinds of semantic relationships. The varying ERP findings here (e.g., the inconsistent taxonomic ERP effects in particular) may in part be due to the inability of monopolar analysis to tease apart inhibitory and facilitatory effects that may co-occur. Using traditional EEG as well as Laplacian transformation, we probe semantic interference and facilitation as associated with taxonomic and thematic semantic relationships to elaborate on the spatio-temporal dynamics of these processes during word production.

1.3 | Laplacian analysis

To counteract the poor spatial resolution in traditional EEG, we used Laplacian transformation in the current study. This technique provides an estimate of the current source density using a double spatial derivative, thus improving the topographical localization of the monopolar EEG recording (Babiloni et al., 2001; Nunez, 1981). The goal of this method is to decrease the spatial blurring of recorded electrical potentials that occur due to the different conduction distortions caused by the cerebrospinal fluid, meningeal layers, skull, and scalp (Babiloni et al., 1996, 2001). As a consequence of this deblurring process, Laplacian analysis can reveal co-occurring effects that may have been obscured in the monopolar analysis. This technique has been previously used in language production studies (Riès et al., 2011, 2015, 2020; Riès, Janssen, et al., 2013; Riès, Xie, et al., 2013) and outside of language (Roger et al., 2010; Tandonnet et al., 2003; Vidal et al., 2000, 2003, 2011) to reveal components occurring at different recording sites and with overlapping time-courses. Laplacian analysis should therefore allow us to observe different semantic effects (i.e., priming and interference) at different recording sites that may be occurring in overlapping time windows.

1.4 | Current study

This study focuses on clarifying the impacts of semantic co-activation on word retrieval in taxonomic versus thematic contexts using electroencephalography. In particular, we focus on the interference and facilitation effects that are tied to taxonomic and thematic relationships, and where these effects stem from in terms of the different stages leading to word production as reflected in ERP components. We directly compare online processing of taxonomic and thematic relationships by analyzing differences in amplitude between conditions in traditional monopolar event-related potentials (ERPs) derived from mastoid referenced EEG, as well as in Laplacian-transformed ERPs with the goal of dissociating temporally overlapping EEG components sensitive to semantic interference from those sensitive to semantic priming. The use of both analysis methods provides us with the advantage of viewing our data from two perspectives.

More specifically, using a PWI paradigm, we compare both taxonomically related and thematically related pairs to their respective matched unrelated word-picture pairs. Importantly, the unrelated pairs consist of the same words and images as the related counterparts but scrambled in order to prevent any possible confounding effects from including different items across conditions. As discussed earlier, the PWI has been used to study taxonomic and thematic relationships previously with mixed findings that are possibly linked to differences in experimental design. In this study, we carefully controlled for these differences as detailed below. Using the PWI paradigm in the current study presents with several benefits including allowing for the creation of 110 carefully controlled stimulus pairs in each condition while still limiting repetition effects in comparison to other paradigms. Crucially, the existence of prior PWI tasks examining taxonomic and thematic relationships (though limited) ensures that we can compare our results to test the efficacy of our methodology and stimuli design.

In order to optimize the comparison between taxonomic and thematic pairs, we use the same pictures in both conditions paired with different distractor words. To circumvent the previously discussed issue of inconsistent stimuli design and to optimize the comparison of semantic context effects between taxonomic and thematic conditions, we will conduct two norming studies prior to running the EEG experiment as well as a corpus linguistic analysis. Our surveys are designed to collect name agreement information for the images as well as relatedness information for the taxonomic and thematic pairs. The aim is to select pictures with high name agreements and pairs considered to be equally highly related in the taxonomically- and thematically related conditions. We use corpus linguistic analysis to quantify the relatedness of the taxonomic and thematic pairs in our study from multiple angles. In particular, we use Resnik scores (Resnik, 1995) based on WordNet's (Miller, 1995) hierarchical organization of semantic networks, and Pointwise Mutual Information (PMI) based on the probability of co-occurrence within text (as in McDonagh et al., 2020). We expect Resnik scores to be higher for taxonomic compared to thematic pairs, given that taxonomic relationships are defined by being part of the same semantic category. By contrast, we expect PMI values to be higher for thematic compared to taxonomic pairs, indicating a higher likelihood of co-occurrence for thematic versus taxonomic pairs given that thematically related words tend to co-occur in scenarios.

Consistent with previous studies, we hypothesize that taxonomic pairs will lead to behavioral interference (Alario et al., 2000; Costa et al., 2005; de Zubicaray et al., 2013) and that thematic pairs will lead to behavioral

facilitation on naming latencies (Alario et al., 2000; Bloem et al., 2004; Costa et al., 2005). As in previous language production studies investigating the impact of semantic relationships using the PWI paradigm, we expect that taxonomically related pairs will be associated with less negative ERPs in time-windows associated with visual processing and early lexical access (i.e., between 150 and 250 ms poststimulus onset, Blackford et al., 2012; De Cesarei et al., 2013; Eddy et al., 2006; Eddy & Holcomb, 2010; Strijkers et al., 2010), indicating less effortful processing. Items in the same category often share visual features, therefore participants' visual processing of a picture may be aided by a previously presented taxonomically related concept. Thematically related concepts may not share the same visual feature overlap but early lexical access is also expected to be facilitated in the case of thematically related concepts, although not as strongly as for taxonomically related concepts. Therefore, we also expect to see a difference in ERP amplitude in this early time-window between the related and unrelated pairs in the thematic condition, although this difference should be smaller than for the taxonomically related pairs. Finally, we expect the effects on ERP amplitude to differ between the taxonomic and thematic conditions in the N400 time window associated with word retrieval processes beginning after initial lexical activation such as lexical selection (i.e., between 300 and 500 ms, Holcomb et al., 2002; Kutas & Federmeier, 2011; Kutas & Hillyard, 1980; Piai et al., 2012). In particular, we expect to replicate previous results showing smaller amplitude in the N400 time window using monopolar analyses (Blackford et al., 2012; Kutas & Federmeier, 2011). In addition to this priming effect, we expect to benefit from the increased topographical localization afforded through Laplacian analyses and find simultaneous opposite effects in the N400 time window. In particular, in the taxonomic condition, we predict increased amplitude in the related compared to unrelated condition over cortical regions previously associated with semantic interference resolution such as the left inferior frontal cortex (i.e., Riès et al., 2015, 2017; Schnur et al., 2009). This effect should not be present in the thematic condition.

2 | METHOD

2.1 | Naming survey

During the formulation of our stimuli, we conducted two surveys. The first, discussed here, was a picture norming survey to ensure high naming agreement for the experimental images.

2.1.1 | Participants

For the picture norming survey, we recruited 21 participants (14 females; average age = 38.3 years; SD = 20.4 years; IQR = 22–60).

2.1.2 | Materials

A total of 177 color images were initially selected for this experiment from the BOSS database (Brodeur et al., 2014) and the internet. The images consisted of animals, food, household items, body parts, and other easily imageable items.

2.1.3 | Procedure

A Qualtrics online survey was created for the norming experiment. Ten participants (six females; average age = 30.4 years; SD = 18.2 years) named list 1 (89 images) and 11 participants (nine females; average age = 48.6 years; SD = 19.6 years) named list 2 (the remaining 88 images). The images were presented one at a time and participants could proceed through the survey at their own pace.

2.1.4 | Results

Naming agreement for both lists combined was 92.64% on average (SD = 13%). After norming, we removed images that had less than 70% naming agreement.

2.2 | Relatedness survey

We conducted a survey to examine whether there was a difference in the degree of perceived semantic relatedness of taxonomic versus thematic pairs. The relatedness survey was performed to make sure that the picture-word pairs in both related conditions in our main experiment would be strongly related pairs. In addition, we wanted to ensure that our results would not be linked to differences in relatedness strength between conditions.

2.2.1 | Participants

For the prime-target word relatedness survey, we recruited 41 participants (34 females; average age = 38.1 years; SD = 20.3 years; IQR = 23–62).

2.2.2 | Materials

Each of the selected images were paired with four words, a taxonomically related word (a word that belongs to the same semantic category and associated with shared semantic features, such as *WOLF* and *DOG*), a thematically related word (a word that occurs together in events or scenarios with the target picture name, such as *LEASH* and *DOG*), an unrelated word drawn from the list of taxonomic primes (to be compared to the taxonomically related pairs), and an unrelated word drawn from the list of thematic primes (to be compared to the thematically related pairs). The related pairs were chosen using the South Florida Free Association Norms database (Appendix B; Nelson et al., 2004) and by our research group. When choosing the prime-target pairs we ensured that none of the prime words began with the same phoneme as the target. Additionally, we avoided thematic prime words indicating elements that could be visible on the target picture (e.g., we would not use the prime-target pair "mane-lion" because a mane is often visible on an image of a lion).

2.2.3 | Procedure

A Qualtrics survey was created to collect relatedness ratings between primes and targets. Each participant rated the association between 179 prime-target pairs on a 7-point Likert scale ranging from highly unrelated to highly related. Participants received one of four lists containing half of the thematically related pairs and half of the taxonomically related pairs. We included moderately related (ranging from 3 to 5 points) filler items, so that not all items would be strongly related or unrelated. First, the prime appeared on the screen for 1 s and was then replaced by the target word. We used word–word relationship rating instead of word-picture relationship rating in order to avoid any possible ambiguity linked to the picture name.

2.2.4 | Results

We found that there was a significant difference in relatedness rating based on type of prime; thematic primes were rated as significantly more related than taxonomic primes (t[311.34] = 5.371, $p < .01$; thematic: average = 6.52, SD = .31; taxonomic: average = 6.34, SD = .35). For the purposes of the ERP experiment, we controlled for relatedness difference between taxonomic and thematic primes. In order to maximize the number of stimuli for accuracy in EEG output, we maintained a minimum of

100 target images and their primes. To balance the relatedness of the lists, we removed thematic pairs that were more than 1.4 standard deviations higher in relatedness rating than taxonomic pairs, as well as taxonomic pairs that were more than two standard deviations higher in relatedness rating than thematic pairs. This allowed for the creation of a stimulus list both balanced in relatedness and sufficient in size.

The finalized stimuli for the experiment included 110 target pictures each paired with a taxonomic prime, thematic prime, and two matched unrelated primes (Table A1). Taxonomic and thematic primes were not significantly different in length (measured in number of letters; $t[207.47] = -0.05$, $p = .96$; thematic: average = 5.12, $SD = 1.21$; taxonomic: average = 5.13, $SD = 1.52$) or frequency (zipf log word frequency scale based on SUBTLWF (Brysbaert & New, 2009); $t(209.71) = 1.78$, $p = .08$; thematic: average = 4.07, $SD = 0.75$; taxonomic: average = 3.91, $SD = 0.61$).

3 | EEG EXPERIMENT METHOD

3.1 | Participants

We recruited 30 (25 females; average age = 23.1 years; $SD = 3.3$ years; $IQR = 21–25$) native English-speaking current and former students of San Diego State University between the ages of 18–30. All participants were right handed, had no history of neurological damage or hearing loss, and had normal or corrected-to-normal vision. The data of two participants were rejected due to technical issues. The data of two more participants were rejected from the analyses due to high EEG artifact rejection rates (>40% of all trials) linked to excessive movement and interference from heartbeat. A fifth participant's data were rejected due to average reaction time more than two standard deviations above the mean of the RTs for the group (average = 781 ms, $SD = 175$ ms). We therefore performed our analyses on the remaining 25 participants (20 females; average age = 23.2 years; $SD = 3.3$ years; $IQR = 21–25$).

3.2 | Design

The order of presentation of the stimuli was mixed pseudo-randomly using Mix (van Casteren & Davis, 2006) which controlled for distance between identical target pictures, identical prime words, relationship type of pairs, semantic category, and phonological onset. We created 12 different lists, each of which were used at least twice across participants. Pictures had an average name agreement of 95.73% ($SD = 8.04\%$). The average relatedness rating for taxonomic

pairs was 6.42 ($SD = .30$), and 6.48 ($SD = .30$) out of seven for thematic pairs. The average relatedness rating for unrelated taxonomic pairs was 1.73 ($SD = 1.04$), and 1.64 ($SD = .94$) for unrelated thematic pairs. To further quantify taxonomic and thematic relatedness we used both Resnik scores (Resnik, 1995) and Pointwise Mutual Information (PMI) (as in McDonagh et al., 2020). Resnik scores were calculated on word pairs in WordNet (Miller, 1995). This measurement evaluates taxonomic similarity because it is based in WordNet's hierarchical organization of semantic networks. The Resnik similarity score represents how related two words are in a taxonomic hierarchy, with 0 indicating no relationship and higher scores indicating more closely related words (McDonagh et al., 2020). PMI serves as an appropriate index for thematic similarity because it calculates the probability that two words co-occur in text. PMI = 0 is a chance level co-occurrence of two terms, a positive PMI score is greater than chance, and a negative PMI score is less than chance. PMI was calculated using Natural Language Toolkit for Python, using a window of five words excluding punctuation on the spoken language data in the Corpus of Contemporary American English (COCA). As predicted, we found a double dissociation between our taxonomic and thematic pairs: taxonomic pairs had higher Resnik scores than thematic pairs (*taxonomic:* average = 4.54, $SD = 3.58$; *thematic:* average = 1.50, $SD = 1.66$; $F[1218] = 65.1$, $p < .01$) and lower PMI scores (*taxonomic:* average = 2.00, $SD = 3.23$; *thematic:* average = 2.90, $SD = 3.57$; $F[1218] = 6.73$, $p = .01$).

3.3 | Procedure

Each participant saw all 110 images four times with each of the possible word primes: taxonomic, thematic, unrelated taxonomic (i.e., taxonomic picture-word pairs scrambled), and unrelated thematic (i.e., thematic picture-word pairs scrambled). Participants were seated comfortably approximately 140 cm from the stimulus monitor in a dimly-lit room separate from the experimenter. Each trial consisted of a prime word presented for 200 ms followed by the target image presented for 300 ms and then a blank screen for 1800 ms during which the participant named the image aloud (they were told to ignore prime words; Figure 1). The stimulus onset asynchrony (SOA) between the prime and target was therefore 200 ms. This SOA was chosen after considering semantic interference and semantic facilitation findings in previous PWI literature, which indicated that both interference and facilitation effects should be observed with an SOA of 200 ms (Alario et al., 2000; Aristei et al., 2011; Blackford et al., 2012; Bloem et al., 2004; de Zubicaray et al., 2013; Hirschfeld et al., 2008; Sailor
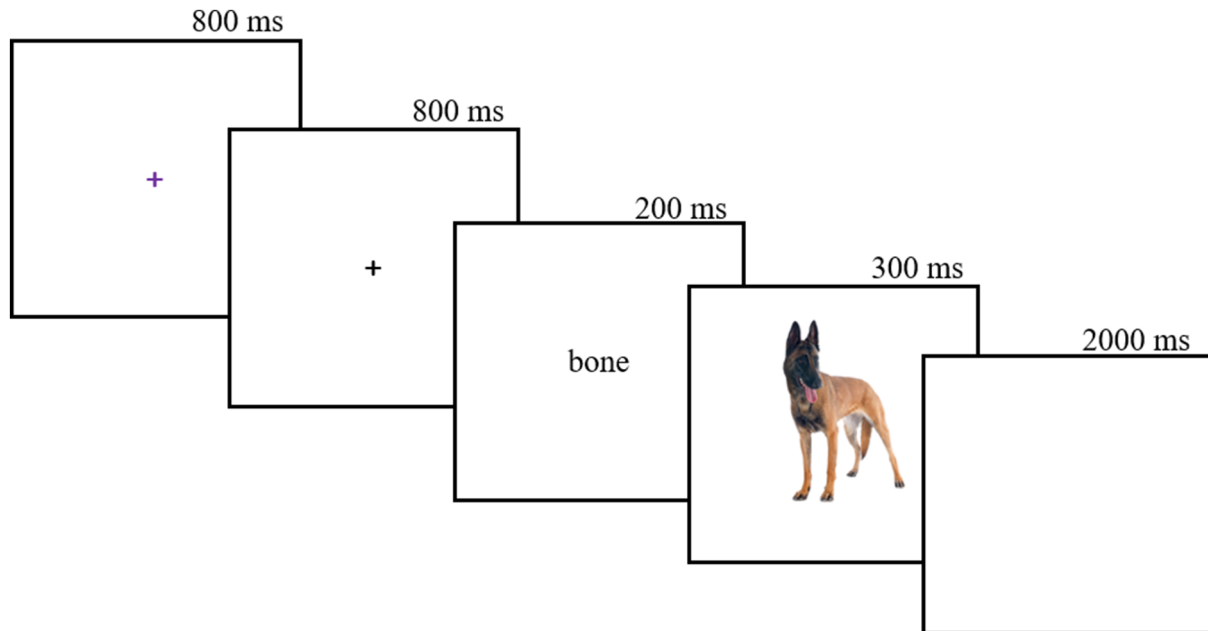
FIGURE 1 Example trial. Each trial consisted of two fixation crosses, a prime word, and the target image. Participants were instructed to blink during the purple fixation cross and to name the image during the white screen
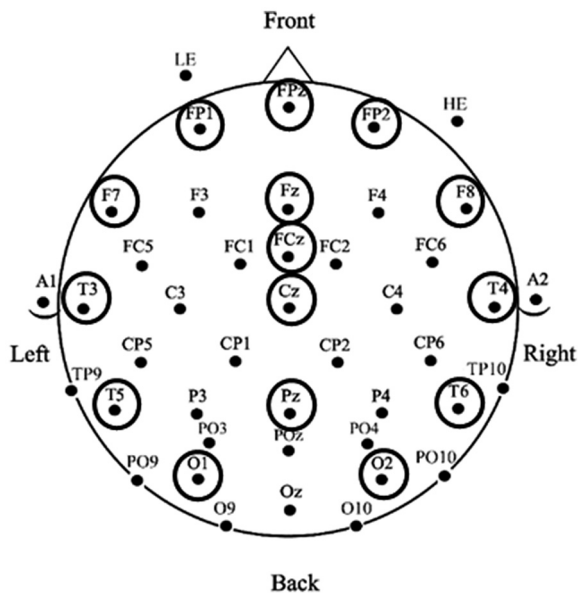

FIGURE 2 EEG recording array. Thirty-nine active electrodes, an electrode on each mastoid (A1, A2), under the left eye (LE), and at the outer corner of the right eye (HE). The left mastoid (A1) served as the reference during recording and analyses. The 15 channels used for the ANOVAs are indicated on the array

by a black fixation cross also displayed for 800 ms. Participants were instructed to try and blink only during the purple fixation crosses as well as during longer blink breaks that occurred approximately every 10–15 trials. There were also five self-paced breaks throughout the experiment. Participants underwent a practice trial with 16 prime-picture pairs before the beginning of the experiment (these pairs were not included in the experiment). We did not familiarize participants with the images to minimize possible effects from repetition priming.

3.4 | EEG recording

Participants were fitted with an elastic electrode cap with 39 active electrodes (Figure 2). EEG was amplified with SynAmpsRT amplifiers (Neuroscan-Compumedics) with a bandpass of DC to 100 Hz and was sampled continuously at 500 Hz. By using a 39-channel cap, we are able to maintain a basis of comparison to previous work in the field that commonly uses 32-channel caps (Chauncey et al., 2009; Declerck et al., 2021a, 2021b; Grainger et al., 2006; McGarry et al., 2021; Meade et al., 2018, 2022).

We also placed an electrode on each mastoid, under the left eye, and at the outer corner of the right eye. The left mastoid served as the reference during recording and analyses. The electrode under the left eye in combination with the electrodes on the forehead were used to identify blinks and the electrode to the side of the right eye

et al., 2009). Images subtended a visual angle of 2.1 degrees in the horizontal and vertical directions. Primes were presented in lowercase black Courier New font at the center of a white screen and subtended a horizontal visual angle of 1.85 degrees or less. Between each trial, a purple fixation cross was displayed for 800 ms followed

identified horizontal eye movements. All electrode impedances were maintained below 2.5 kΩ (with the exception of one participant who had impedances of below 20 kΩ) by using saline gel (Electro-Gel).

3.5 | Behavioral data analysis

For the remaining 25 participants, we analyzed mean naming latencies on correctly answered trials in each condition. Correct responses were defined as answers matching the picture name with the highest name agreement for a given item. We accepted as correct semantically identical names for an item (e.g., plane for airplane, bunny for rabbit, etc.). Any response that included anything besides the name of the item was considered an error (e.g., stutter, semantically different word, hesitation such as "uh"). Responses outside of 300–1800 ms after target onset were excluded from analysis. Statistical analysis was performed within R version 3.6.0 using the packages "lme4" to compute the mixed effect models (Bates et al., 2014a, 2014b) and "car" to compute analysis of deviance tables for the fixed effects of the mixed effect models (Fox & Weisberg, 2011). We report Wald chi-square values and p values from the analysis of deviance table, as well as raw β estimates (β_{raw}), standard errors, Wald Z, and associated p values for significant and marginally significant effects. The individual reaction times (RTs) were inverse-transformed to reduce skewness and approach a normal distribution. The analyses were performed on inverse-transformed RTs. Naming latency data were analyzed with linear mixed-effects models, testing for main effects of Type (Taxonomic, Thematic) and Relatedness (Related, Unrelated) and their interaction as within-participant factors and we had intercepts for participants and picture name as random effects as well as by-subject and by-target random slopes for Type by Relatedness. We analyzed the accuracy data using logistic mixed-effects models (Baayen et al., 2008; Jaeger, 2008). We tested for main effects of Type and Relatedness and their interaction as within-participant factors and we had intercepts for participants and picture name as random effects as well as by-subject and by-target random slopes for Type by Relatedness.

3.6 | ERP data analysis

The ERP analyses presented in this paper are time-locked to the onset of the presentation of the target image presented to participants. We examine the 150–250 and 300–500 ms epochs as it has been established that the effect of semantic manipulations can be observed on the amplitude of ERP components such as N100, N400, P100, etc.

(Blackford et al., 2012; Kutas & Hillyard, 1980). Both monopolar and Laplacian analyses were conducted on the data collected in this experiment. We will discuss each in turn in the following sections.

3.6.1 | Monopolar analysis

Across the 25 participants, artifact contamination from eye movement and speech led to the rejection of 7.6% of trials on average. As in a number of previous language processing studies from our research group, the ERP data from a representative sub-array of 15 channels were used for analysis (Chauncey et al., 2009; Grainger et al., 2006). This sub-array consisted of three columns over left, center, and right hemisphere locations, each with five electrode sites extending from the front to the back of the head (Figure 2).

The data were analyzed using repeated measures omnibus ANOVAs with the within-participant factors of Relatedness (Related, Unrelated), Prime Type (Taxonomic, Thematic), Laterality (left, midline, right), and Anteriority of electrode sites (Prefrontal, Frontal, Central, Parietal, and Occipital). Planned follow-up ANOVAs with the within-participant factors of Prime Type (Taxonomic Related OR Thematic Related, Taxonomic Unrelated OR Thematic Unrelated), Laterality (left, midline, and right), and Anteriority (Prefrontal, Frontal, Central, Parietal, and Occipital) were also conducted. Only correct trials were used during ERP analyses. The dependent measures were the mean amplitude measurements in the time windows: 150–250 and 300–500 ms poststimulus (target image) onset. This 150–250 ms time window captures components associated with early visual feature processing (Blackford et al., 2012; De Cesarei et al., 2013; Eddy et al., 2006; Eddy & Holcomb, 2010) and early lexical access (Blackford et al., 2012; Eddy et al., 2006; Eddy & Holcomb, 2010; Strijkers et al., 2010). The 300–500 ms time window is centered on the N400, which is an established component in language research and has been shown to be sensitive to lexico-semantic processing (Kutas & Federmeier, 2011; Kutas & Hillyard, 1980). According to prior language research involving images, an early N300 may be present in addition to the N400 and may be more sensitive to early semantic processing involving semantic features (Blackford et al., 2012; Eddy et al., 2006; Eddy & Holcomb, 2010). As in these previous studies, the epochs we have selected are relevant time frames for the detection of these components.

3.6.2 | Laplacian analysis

In speech production EEG experiments, experimenters have to take artifacts from speech articulation into account

on top of the artifacts produced from blinking, horizontal eye movements, etc. Speaking in particular induces large amounts of EMG activity that heavily contaminates the EEG signal (Vos et al., 2010). Articulation-related EMG activity predominantly occurs closer to vocal onset (van der Linden et al., 2014). Our chosen analysis windows, 150–250 and 300–500 ms, end earlier than two standard deviations below the mean voice onset time (average = 781 ms, SD = 125 ms). This makes it unlikely that there was any significant articulation-related artifact in the monopolar ERPs up to the point of analysis. However, Laplacian transformation is particularly sensitive to artifacts (Tandonnet et al., 2005; Vidal et al., 2003), therefore we implemented additional processing steps prior to Laplacian analyses. We used Blind Source Separation based on Canonical Correlation Analysis, or BSS-CCA (using the AAR toolbox for EEGlab by Gómez-Herrero, 2007), to reduce the impact of EMG artifacts from speech articulation in the EEG signal as in (De Clercq et al., 2006; Hallez et al., 2009; Riès et al., 2011, 2015, Riès, Janssen, et al., 2013; Riès, Xie, et al., 2013; Vos et al., 2010). Any artifacts remaining after BSS-CCA were rejected by hand on a trial-by-trial basis. See Supplementary Information for analyses conducted on monopolar data after artifact rejection with BSS-CCA.

After artifact rejection, we then used Laplacian transformation (providing an estimate of the current source density, CSD) in BrainVision Analyzer 2.1 (BrainVision Analyzer, Brain Products GmbH, Gilching, Germany). Laplacian transformation has been shown to increase the spatial resolution of the EEG signal, providing a good estimation of the corticogram (Nunez & Srinivasan, 2006).

As in previous studies (Riès et al., 2011, 2015, 2020; Riès, Janssen, et al., 2013; Riès, Xie, et al., 2013), Laplacian transformation was applied to each participant's individual averages. Then, a grand average was created from those individual averages. Because the voltage distribution is only known at the electrodes, the spherical spline interpolation method is used prior to the application of the spherical Laplace operator in order to estimate the entire voltage distribution (Perrin et al., 1989). Then, second derivations in two dimensions of space were computed (Legendre polynomial: 15° maximum). We chose three for the degree of spline because this value best minimizes errors (Perrin et al., 1987). We assumed a radius of 10 cm for the sphere representing the head. The resulting unit was µV/cm².

The enhanced topographical localization from Laplacian transformation allowed us to examine ERPs at each electrode site of interest. Linguistic processes involved in picture naming are often described as left-lateralized and have been described at temporoparietal, lateral frontal, and medial frontal sites (Riès, Janssen, et al., 2013; Riès, Xie, et al., 2013), therefore we chose to conduct our main analysis on the pre-identified electrode sites which showed indication of differences between conditions on the grand averages (T3, CP5, and FC5). In particular, a rising negative component has been previously described during picture naming at the left frontal site FC5 (Riès, Janssen, et al., 2013). We also conducted statistical analyses on the sites contralateral to these electrodes (T4, CP6, and FC6) but observed no effects at the contralateral sites. Accordingly, we present the results from the analysis conducted at the left lateral sites T3, CP5, and FC5.

To allow for easier comparison with the monopolar results, we used the same epochs that were used in the monopolar analysis in the analysis of the Laplacian-transformed ERPs: 150–250 and 300–500 ms. The surface area under the curve was calculated in all four conditions for each participant at the electrodes of interest. The EEG data were analyzed using Student's t tests or ANOVAs for comparisons of more than two means.

4 | RESULTS

4.1 | Behavioral results

Overall, the naming latencies in the taxonomic conditions (related and unrelated) were slower than the naming latencies in the thematic conditions (related and unrelated) ($X^2[1,25]$ = 30.44, $p < .01$; β_{raw} = 4.24×10^{-5}, SE = 7.69×10^{-6}, Wald Z = 5.52; mean RTs = 784.2 ms, 771.2 ms). In addition, there was a significant interaction between relatedness (related and unrelated) and type of prime (taxonomic and thematic), indicating the relationship between the taxonomic related and unrelated conditions was different from the relationship between the thematic related and unrelated conditions ($X^2[1,25]$ = 18.33, $p < .01$; β_{raw} = -4.06×10^{-5}, SE = 9.48×10^{-6}, Wald Z = -4.28). Planned follow-up analyses were used to break down this interaction. Specifically, for taxonomic pairs, naming latencies were significantly slower (by on average 14 ms) for related than unrelated pairs ($F[1, 25]$ = 5.96, $p < .05$; *taxonomic related:* mean RT = 791.4 ms; SD = 94.2 ms; *taxonomic unrelated:* mean RT = 776.99 ms; SD = 84.64 ms), in the direction of semantic interference. By contrast, naming latencies for thematic pairs were significantly faster (by on average 10 ms) for related than unrelated conditions ($F[1, 25]$ = 7.99, $p < .01$; *thematic related:* mean RT = 766.4 ms; SD = 90 ms; *thematic unrelated:* mean RT = 776.1 ms; SD = 83.1 ms), in the direction of semantic facilitation. Participants had high accuracy rates (average = 92.3% correct; SD = 25.9%). Only a marginal effect of type of prime was found on accuracy rates ($X^2[1,25]$ = 2.82, p = .093), which was due to accuracy

(a) Reaction Time (Relatedness x Prime Type)

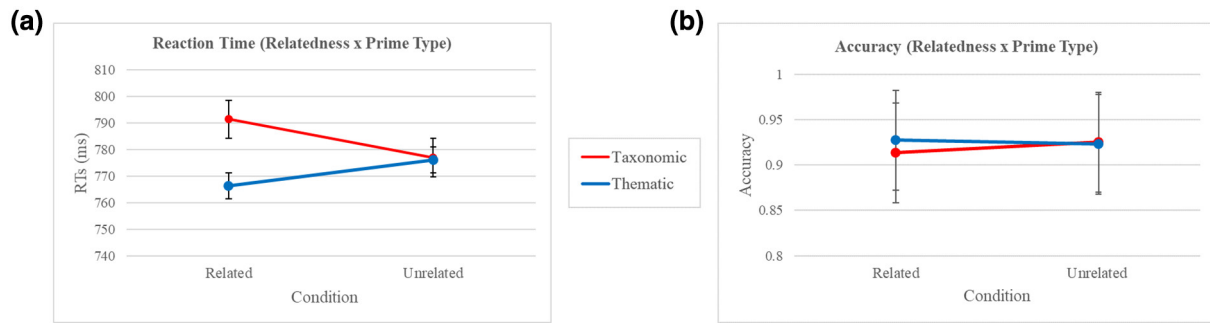**(b)** Accuracy (Relatedness x Prime Type)

FIGURE 3 (a) Reaction times for relatedness by prime type interaction. (b) Accuracy rates for relatedness by prime type. Taxonomic conditions are depicted in red and thematic conditions are depicted in blue. Standard error bars are included on each average

rates being higher for thematic pairs versus taxonomic pairs ($\beta_{raw} = 0.325$, $SE = 0.193$, Wald $Z = 1.61$, $p = .093$). There was no main effect of relatedness ($X^2[1,25] = 2.36$, $p = .12$) and no interaction between relatedness and type ($X^2[1,25] = 2.49$, $p = .11$) (see Figure 3b).

4.2 | Monopolar EEG results

Voltage maps in the 150–250 and 300–500 ms time windows, as well as grand averages, time-locked to the presentation of target images are plotted in Figure 4.

4.2.1 | Early effects: 150–250 ms

The omnibus ANOVA showed a main effect of relatedness ($F[1,24] = 16.78$, $p < .01$), as well as a three-way interaction between relatedness, laterality, and anteriority ($F[8192] = 7.34$, $p < .01$). This indicated that unrelated conditions elicited a greater negativity than related conditions, overall, but especially at anterior midline sites. There was no significant main effect of type of prime ($F[1, 24] = 3.01$, $p = .096$) nor interaction of prime type and relatedness ($F[1, 24] = 3.26$, $p = .084$). In the follow-up ANOVA for the taxonomic condition alone, there was an effect of relatedness ($F[1,24] = 15.77$, $p < .01$); unrelated pairs elicited a greater negativity than related pairs. Again, there was a three-way interaction in relatedness, laterality, and anteriority ($F[8192] = 6.8$, $p < .01$). Similarly, as in the general analysis, the difference in relatedness occurred especially at the anterior midline sites. In the analysis of the thematic condition, there was no main effect of relatedness ($F[1, 24] = 2.75$, $p = .11$). However, there was a three-way interaction between relatedness, laterality, and anteriority, which indicated that the relatedness effect was in fact limited to left lateral anterior electrodes ($F[8, 192] = 3.13$, $p < .05$). For these electrode sites, unrelated pairs elicited a greater negativity than related pairs.

4.2.2 | The N400: 300–500 ms

The omnibus ANOVA in this window revealed a main effect of relatedness ($F[1,24] = 23.97$, $p < .01$) as well as a three-way interaction between relatedness, laterality, and anteriority ($F[8192] = 3.89$, $p < .01$). As in the earlier window, there was no main effect of prime type ($F[1, 24] = .97$, $p = .33$) nor interaction between prime type and relatedness, suggesting that the relationship between the related and unrelated pairs did not differ significantly between the taxonomic and thematic conditions ($F[1, 24] = .75$, $p = .39$). In the taxonomic condition, there was a main effect of relatedness with the unrelated pairs eliciting a significantly larger negativity than the related pairs ($F[1,24] = 10.65$, $p < .01$). There was also a three-way interaction between relatedness, laterality, and anteriority ($F[8192] = 2.07$, $p < .05$). The effect was pronounced at left anterior electrode sites. Unlike in the earlier time window, there was a main effect of relatedness ($F[1,24] = 20.07$, $p < .01$) in the thematic condition; unrelated pairs elicited a greater negativity than related pairs. There was also a three-way interaction between relatedness, laterality, and anteriority ($F[8192] = 2.77$, $p < .01$). Again, the effect was most pronounced at left anterior electrode sites.

4.3 | Laplacian EEG results

Voltage maps in the 150–250 and 300–500 ms time windows, as well as waveforms, time-locked to the presentation of target images are plotted in Figures 5 and 6.

4.3.1 | Early effects: 150–250 ms

At electrode T3, during the 150–250 ms time window, in the taxonomic condition, unrelated pairs elicited a greater negativity than the related pairs ($t[25] = -2.86$, $p < .01$). In the thematic condition, there was no significant difference in amplitude between the related and unrelated
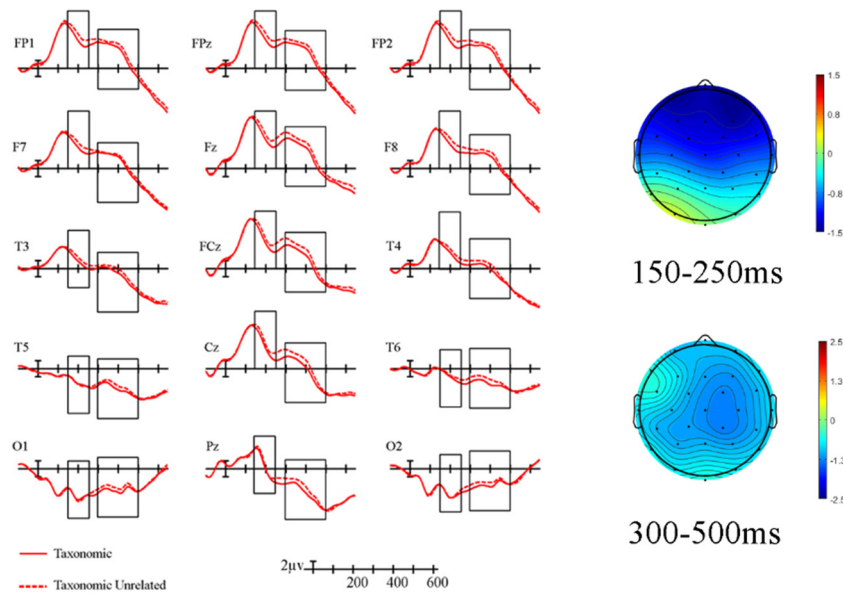
Taxonomic

Thematic

FIGURE 4 Monopolar ERP waveforms and voltage difference maps for the 150–250 and 300–500 ms time-windows after stimulus onset. Both epochs (150–250 and 300–500 ms) have been highlighted on the waveforms. *Taxonomic (red)*: In both the 150–250 and 300–500 ms epochs, the unrelated pairs elicited a greater negativity. *Thematic (blue)*: In the 150–250 ms epoch, unrelated pairs localized to the left anterior electrodes elicited a greater negativity. In the 300–500 ms epoch, unrelated pairs elicited a greater, more widespread negativity. Related conditions are depicted by solid lines and unrelated conditions are depicted by dotted lines. Note that negative is plotted up in this diagram. The significance stars depicted were derived from the ANOVAs; these values are uncorrected and provide a general map of the direction of the effects
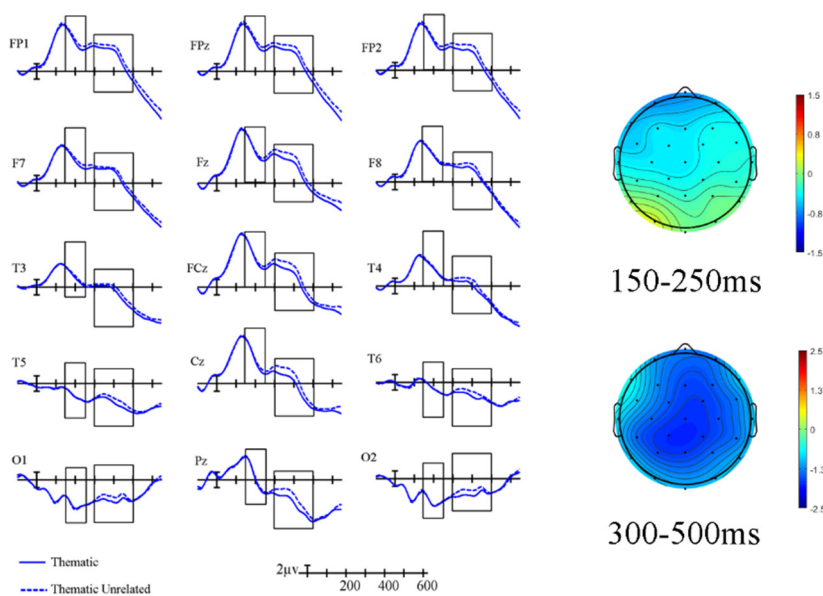
pairs ($t[25] = -1.67$, $p = .11$). This is in agreement with the early results we observed in our monopolar analysis.

4.3.2 | The N400: 300–500 ms

The same effects reported in the monopolar analysis were found at electrode CP5 after Laplacian transformation (Figure 6): the unrelated pairs elicited greater negativity than the related pairs in both the taxonomic and thematic conditions ($t(25) = -3.04$, $p < .01$ and $t(25) = -2.94$, $p < .01$, respectively). However, a different effect was observed at

electrode FC5 (Figure 6), a more anterior electrode site. In the taxonomic condition, the related pairs elicited a greater negativity than the unrelated pairs ($t(25) = 2.73$, $p < .05$).

5 | DISCUSSION

The aim of the present study was to investigate how different conceptual relationships influence the different stages of speech production through measuring ERPs and naming latencies to pictures in a PWI paradigm. Importantly, we used traditional monopolar analysis as well as
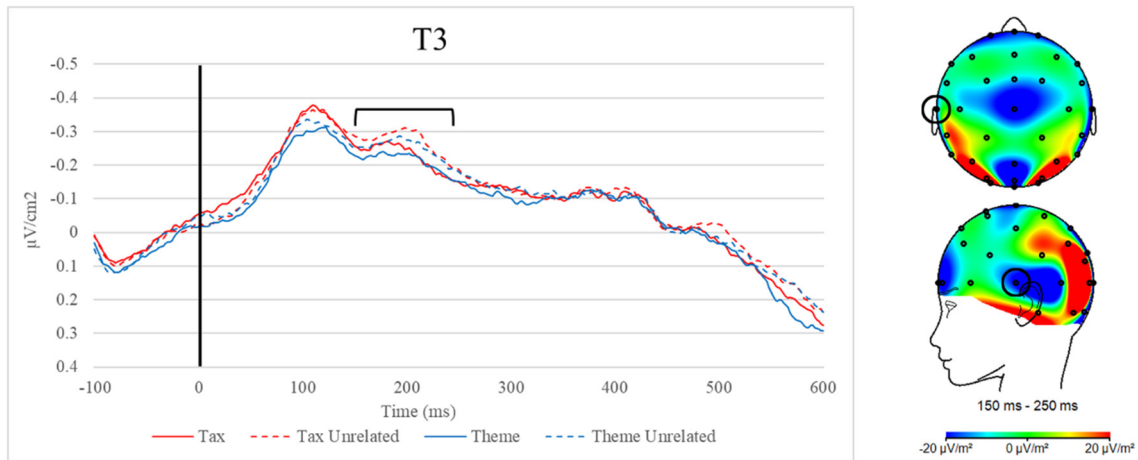
FIGURE 5 Laplacian-transformed ERP waveforms at electrode T3, pictured on scalp (right); in the 150–250 ms epoch, unrelated pairs elicit greater negativity than the related pairs in the taxonomic condition, as seen in the monopolar analysis. Taxonomic conditions are depicted in red and thematic conditions are depicted in blue. Related conditions are depicted by solid lines; unrelated conditions are depicted by dotted lines. Note that negative is plotted up in this diagram
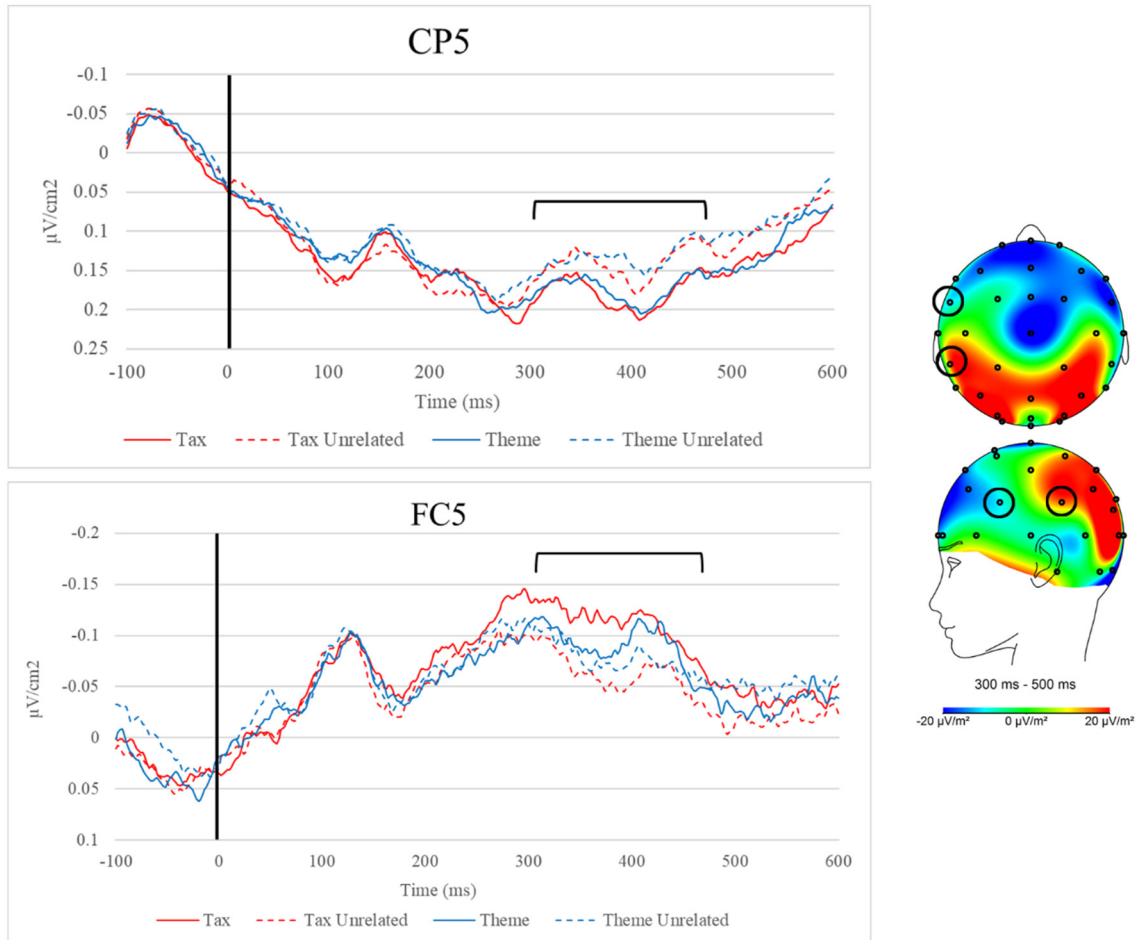
FIGURE 6 Laplacian-transformed ERP waveforms at electrode CP5 (top) and FC5 (bottom). At CP5, pictured on scalp (left, posterior), unrelated conditions elicit greater negativity than the related conditions, as seen in the monopolar analysis. At FC5, pictured on scalp (left, anterior), the taxonomic-related condition elicited significantly greater negativity than the unrelated condition (left). Taxonomic conditions are depicted in red and thematic conditions are depicted in blue. Related conditions are depicted by solid lines; unrelated conditions are depicted by dotted lines. Note that negative is plotted up in this diagram

Laplacian transformation allowing us to examine spatially deblurred event-related components. Similar to previous studies (Alario et al., 2000; Bloem et al., 2004; Costa et al., 2005), we found opposite effects of taxonomic and thematic relationships on naming latencies. Taxonomic relationships led to semantic interference while thematic relationships led to semantic facilitation. Monopolar EEG analyses showed that unrelated pairs elicited a greater negativity than related pairs in the taxonomic condition in both time windows (150–250 ms, 300–500 ms). In the thematic condition, unrelated pairs also elicited a larger early negativity but over a more spatially restricted left lateral group of electrodes (150–250 ms). This effect became widespread in the later time window (300–500 ms). Laplacian analyses revealed similar findings in these time windows with the exception of an additional greater left frontal negativity for related than unrelated pairs in the taxonomic condition at electrode FC5 (300–500 ms). We address the implications of our behavioral, monopolar, and Laplacian analysis findings in turn.

5.1 | Behavioral analysis

Naming latency results showed a 14 ms average increase for the taxonomically related pairs compared to the unrelated pairs. This interference effect presumably reflects more effortful processing when naming images preceded by a taxonomically related word. Conversely, there was a 10 ms average decrease in naming latencies for the thematically related pairs compared to the unrelated pairs. This facilitation effect presumably reflects easier processing when naming images preceded by a thematically related word. These findings replicate those of previous naming studies (e.g., Alario et al., 2000; Bloem et al., 2004; Costa et al., 2005; Rabovsky et al., 2016).

Whether the end result of our speech production processes is facilitation or interference is dependent on the characteristics of the semantic relationships between the words being studied. The model proposed by Rabovsky et al. (2016) places the number of semantic features (NOF) and intercorrelational feature density at the core of the different behavioral outcomes observed in thematic versus taxonomic contexts. Taxonomically related words tend to share a large number of features because they belong to the same semantic category. This important number of shared features has been associated with increased activation of semantic neighbors sharing these features during production. This co-activation of semantically related neighbors is assumed to be the cause of the semantic interference effect observed in taxonomic contexts. Conversely, thematically related words belong to different semantic categories and do not typically share

a large number of features. Therefore, thematic relationships do not typically activate as large of a lexical cohort as taxonomic relationships (Rabovsky et al., 2016; Rose et al., 2019).

However, another complementary interpretation for the facilitation effect in thematic contexts may be linked to predictability. Indeed, our stimuli showed a double dissociation between Resnik scores (Resnik, 1995), which measure relatedness based on WordNet's hierarchical network of semantic relations (Miller, 1995), and PMI, which measures relatedness based on the probability of two words co-occurring in a text. Thematically related words were found to be more likely to co-occur in text within five words of one another compared to taxonomically related words. This higher co-occurrence may allow participants to form expectations which will be met when seeing a word followed by an image representing a thematically related concept, hence the facilitation effect observed on reaction times. For taxonomic pairs, these expectations may not be as strong and instead the large co-activated cohort of semantically related alternatives makes selecting the correct response more difficult (McDonagh et al., 2020).

5.2 | Monopolar analysis

In the early time window, 150–250 ms post target image presentation, the results showed a widespread greater negativity for unrelated than related pairs in the taxonomic condition. In the thematic condition, this effect was more localized and restricted to left anterior sites. Previous picture naming studies demonstrated that early components were associated with early visual feature processing in epochs overlapping with our 150–250 ms time window (Blackford et al., 2012; De Cesarei et al., 2013; Eddy et al., 2006; Eddy & Holcomb, 2010). In addition, access to the structural semantic features that are specific to visual objects and early lexical access have also been proposed to occur within this same time window (Blackford et al., 2012; Eddy et al., 2006; Eddy & Holcomb, 2010; Strijkers et al., 2010). According to language production models, the prime word activates a cohort of semantic features which are shared with other words. This allows for an initial spreading of activation to lexical representations in the same semantic cohort. Taxonomically related words share a larger cohort of shared perceptual and semantic features than thematically related words as proposed by Rabovsky et al., 2016 and as demonstrated through our Resnik score analysis. Our results are therefore in agreement with this proposal.

Then, we considered the N400 time window spanning between 300 and 500 ms poststimulus presentation (Kutas & Federmeier, 2011). The N400 is a negative-going

waveform that peaks around 400 ms poststimulus presentation. This ERP component is frequently modulated by changes in the semantic context of stimuli. When stimuli are preceded by semantically related content, whether words or images, the N400 has been shown to be attenuated in amplitude in comparison to when stimuli are preceded by unrelated content (Bentin et al., 1985; Johnson et al., 1996; Kutas & Federmeier, 2011). Unrelated, semantically inappropriate, or difficult to process content tends, on the contrary, to increase the amplitude of the N400 (Kutas & Hillyard, 1980). In our study, we found that in this 300–500 ms time window, unrelated pairs elicited a greater negativity than related pairs in both the taxonomic and thematic conditions. This is in agreement with the idea that related semantic context helps lexical processing for both taxonomic and thematic relationships. These findings from monopolar analyses suggest highly similar processing for taxonomic and thematic relationships and thus would need to be represented by a model that accounts for this similarity. The controlled semantic cognition (CSC) framework (Jefferies et al., 2020) proposes an equivalent response for taxonomic and thematic relationships in the anterior temporal lobe (ATL). However, when semantic control demands are high the CSC predicts a stronger response in the posterior middle temporal gyrus (pMTG) and inferior frontal gyrus (IFG). We must consider the more focal effects from Laplacian transformation before drawing conclusions regarding the CSC framework. However, the allowance for simultaneous engagement of overlapping and distinct brain regions is promising.

The effect in the taxonomic condition persisted from the 150 to 250 ms window we examined. This is in agreement with EEG studies that have shown that activity associated with early processes does not necessarily stop when activity associated with downstream processes begin (Hassan et al., 2015; Janssen et al., 2020), supporting an interactive view of processing stages in language production (Dell et al., 2013). The amplitude reduction in the related versus unrelated conditions for thematic pairs was more widespread than in the earlier time window. A possible interpretation of this effect could be linked to predictive processing. Indeed, we found in our PMI analysis that thematically related words were found to be more likely to co-occur in text compared to taxonomically related words. The N400 has been shown to be attenuated in contexts where participants are able to predict the upcoming piece of information, such as in sentence completion or priming studies (Kutas & Federmeier, 2011; Lau et al., 2013). This would support the more widespread ERP amplitude reduction in the thematic condition in the 300–500 ms time window compared to the taxonomic condition.

At this point however, it is unclear which process may be sensitive to semantic interference in the taxonomic condition given that all observed effects on the monopolar ERPs suggest less effortful visual and lexico-semantic processing in the related than unrelated conditions. As mentioned in the introduction, mixed ERP findings have been reported as a result of semantic context manipulation. Reduced ERP amplitudes in related versus unrelated conditions have been found in thematic relationships, but not in taxonomic relationships in the few studies directly comparing these relationships (Hirschfeld et al., 2008; Wamain et al., 2015); although there has also been evidence of reduced ERP amplitudes in taxonomically related compared to unrelated conditions in other studies (e.g., Blackford et al., 2012; Kutas & Federmeier, 2011). One possible reason explaining these differences may be linked to the methods used. In particular, in traditional monopolar analyses spatial resolution is usually low due to the diffusion of the electrical currents through the tissue layers and cerebrospinal fluid separating the brain from the recording sites. In order to investigate these semantic context effects further, we conducted analyses on the Laplacian-transformed ERPs in order to separate neighboring components potentially sensitive in opposite ways to semantic contexts (Nunez & Srinivasan, 2006; Riès et al., 2011).

5.3 | Laplacian analysis

Laplacian transformation increases topographical selectivity by effectively filtering out spatially diffuse features of the EEG data (Cohen, 2014). This technique has been shown to increase the topographical localization of the ERPs, providing a good estimation of the corticogram, which allowed us to examine more focal components that may have been undetectable in the monopolar analyses (Luck, 2014; Nunez & Srinivasan, 2006; and as in Riès et al., 2011). In the Laplacian analysis, we focused on the same time windows as in the monopolar analysis to facilitate the comparison of the results. In the early time window, between 150 and 250 ms, we found results consistent with our findings on the monopolar ERPs. We found a similar relatedness effect, meaning a larger amplitude for unrelated pairs than related pairs localized to a left temporal recording site in the taxonomic condition. The left temporal cortex has often been associated with lexical access (Baldo et al., 2013; DeLeon et al., 2007; Trebuchon-Da Fonseca et al., 2009). Patients with lesions in the left posterior temporal cortex have been shown to have lexical access deficits in both production (Baldo et al., 2013; DeLeon et al., 2007) and comprehension (Dronkers et al., 2004). Although the spatial resolution remains limited even following Laplacian transformation, the fact that the activity we found at this left temporal site during speech

production is sensitive to semantic relatedness suggests that this activity is an indicator of early lexical access.

In the N400 time window, there were differences between related and unrelated pairs that varied between the taxonomic and thematic conditions. In the thematic condition, unrelated pairs elicited a greater negativity than related pairs. This effect was localized to a left parietal recording site (CP5). Previous fMRI and eye tracking research have found links between the processing of thematic relationships and structures along the dorsal processing route (Kalénine et al., 2009; Mirman et al., 2017; Mirman & Graziano, 2012; Schwartz et al., 2011).[1] In particular, using eye tracking, individuals with lesions in BA 39 and the surrounding temporo-parietal cortex regions have been shown to have reduced and delayed activation of thematic relationships and no difference in activation of taxonomic relationships when compared to the control group, indicating that the temporoparietal cortex may play an important role in the processing of thematic relationships (Mirman & Graziano, 2012). Interestingly, the inferior parietal cortex is also involved in forming expectations and prediction during language comprehension (Obleser & Kotz, 2010), anticipatory processes and predictive mechanisms during early action planning (Fontana et al., 2012), and discourse level prediction (Kandylaki et al., 2016). The observed attenuated negativity at a left parietal recording site in the same time window as the N400 (also shown to be sensitive to predictability, see above) for thematically related compared to unrelated pairs may indicate that participants are forming an expectation for the picture name following the word in the thematic condition.

Our results showed that both taxonomically- and thematically related conditions were associated with reduced ERP amplitude compared to unrelated conditions at CP5. The dual-hub theory would however anticipate this effect to be exclusive to thematic relationships. The CSC framework (Jefferies et al., 2020), mentioned earlier, predicts equivalent responses for both types of semantic relationships in the temporoparietal region as we see here. The CSC framework allows for the possibility that different semantic relationships simultaneously engage overlapping and distinct regions. Specifically, the CSC proposes an equivalent response for taxonomic and semantic relationships in the anterior temporal lobe (ATL) and a stronger response in the posterior middle temporal gyrus (pMTG) and inferior frontal gyrus (IFG) when semantic control demands are high.

Finally, in the 300–500 ms time window, at a left frontal recording site (FC5), related pairs elicited a greater negativity than unrelated pairs in the taxonomic condition. Left frontal activity at the FC5 site has been previously described in the context of language production (Riès, Janssen, et al., 2013). The function of this EEG component has not been agreed upon, but we can consider different possibilities by examining the functions typically associated with the left frontal region. From previous fMRI and lesion study research, activity in the left frontal region has been associated with cognitive control processes allowing individuals to overcome interference from semantically related alternatives for lexical selection (Riès et al., 2015, 2017; Schnur et al., 2005, 2006, 2009; Thompson-Schill et al., 1998). The nature of the left frontal cognitive control mechanism proposed to be involved differs between studies, with some suggesting a booster mechanism helping to tease representations apart (Oppenheim et al., 2010), a task biasing mechanism (Belke & Stielow, 2013), a more domain general proactive control mechanism (Jonides & Nee, 2006; Kan & Thompson-Schill, 2004; Riès et al., 2014), or a decision threshold adjustment mechanism (Anders et al., 2015, 2017). The Laplacian-transformed activity we observed at this left frontal site may be reflecting the engagement of left frontal regions to overcome interference. This left frontal effect was only observed in the context of taxonomically related pairs, and not thematically related pairs. This suggests that the left frontal cognitive control mechanism involved to overcome interference between semantically related representations may be necessary particularly in the taxonomically related context but not in the thematically related context. This is also in agreement with dissociations in the processing of taxonomic and thematic relationships between patients with anterior versus posterior lesions (Mirman & Graziano, 2012; Schwartz et al., 2011).

It is also a possibility that ERP effects observed across taxonomic and thematic relationships could be impacted by individual differences in semantic network organization, reading and language ability, and individual variances in similarity judgments between taxonomic and thematic relationships (as seen in Honke et al., 2020). Taxonomic and thematic similarity judgment have been shown to predict ERP amplitude during passive word reading (Honke et al., 2020). This could be contributing to the differences observed between the conditions and is important to take into consideration when developing future studies.

Most notably, using Laplacian transformation allowed us to dissociate opposite effects in the same time window

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[1]This parietal (dorsal) versus more ventral distribution of effects in thematic versus taxonomic conditions respectively is in agreement with the notion that thematic pairs often contain more manipulable items whereas taxonomic pairs often contain more non-manipulable and living items (Mirman et al., 2017). In our study, there were indeed more living concepts in the taxonomic condition ($X^2(1, 220) = 10.10$, $p < .01$, $\beta_{raw} = 1.12$, $SE = 0.35$, Wald $Z = 3.18$, $p < .01$; see Table A2 in Appendix), but there were more non-manipulable than manipulable items in the thematic condition ($X^2(1, 220) = 5.93$, $p < .05$, $\beta_{raw} = 0.67$, $SE = 0.28$, Wald $Z = 2.44$, $p < .05$; see Table A2 in Appendix).

that were not visible on traditional monopolar ERPs which is a novel finding. We note that the spatial resolution of the Laplacian-transformed ERPs would have been better with a higher number of channels but that it was already increased with the number of channels we used compared to monopolar ERPs as shown by Babiloni et al. (1996).

The presence of both effects in the same time window is in agreement with the idea that facilitation and interference occur concurrently during speech production, as suggested by Rabovsky et al. (2016). Our electrophysiological results are also in agreement with those of Piai et al. (2014) who used magnetoencephalography (MEG) to compare brain responses to taxonomically related and unrelated prime word-picture pairs. Their results showed that activity phase-locked to the stimulus (evoked activity) was larger on unrelated than related trials, occurring in the left temporal cortex and peaking at 400 ms. This effect was in the same time window as the effect we observed in the monopolar analysis and at the left temporal site in the Laplacian analysis. Non-phase-locked activity (induced activity), alternatively, was larger on related than unrelated trials from approximately 350 to 650 ms poststimulus onset and localized to the left superior frontal gyrus. These results, which are largely aligned to our present results, suggested that different types of brain activities are sensitive to semantic relatedness in different ways in similar time windows but different brain regions. Finally, these results also parallel those of Riès et al. (2017), which showed concurrent semantic context effects in both the direction of facilitation and interference using intracranial EEG and the blocked cyclic picture naming paradigm contrasting taxonomically related versus unrelated contexts. This is again in agreement with a more interactive rather than strictly serial view of processing stages in language production. Importantly, this study showed a large semantic interference effect at left frontal recording sites (Riès et al., 2017).

Interestingly, the results from the Laplacian analyses follow the pattern of results from the traditional monopolar analyses in many aspects. The greater negativity for unrelated pairs in the taxonomic condition prior to 300 ms was consistent between analysis methods. However, the ability to examine more focal effects following Laplacian transformation led to a divergence in results. Results from the monopolar analysis did not show different effects for the thematic and taxonomic conditions in the time window spanning from 300 to 500 ms poststimulus presentation. However, Laplacian analyses revealed opposite effects in the same time window at different recording sites. The left temporoparietal results were in agreement with the monopolar finding in that both unrelated conditions elicited a greater negativity than related conditions. Contrastively, at the left frontal recording site, taxonomically related

pairs elicited a greater negativity than unrelated pairs. This was not the case for the thematically related pairs. These results demonstrate that it is not simply that taxonomic relationships are associated with more processing difficulty than thematic relationships at every stage of the word production process. The results reveal that overlapping effects are occurring during lexical retrieval: left frontal cognitive control engages to support the resolution of semantic interference associated with the processing of taxonomic relationships while left posterior regions simultaneously support lexical activation facilitated by the presence of semantically related neighbors. These simultaneous effects would not have been documented without the use of Laplacian transformation. The results from monopolar analysis were not invalidated by the introduction of a second analysis method but supplemented and further clarified.

6 | CONCLUSION

In conclusion, our results suggest that when we speak, spreading activation between semantically related concepts facilitates lexical access in the brain whether or not the relationship is thematic or taxonomic, as indicated by the early ERP effects between 150 and 250 ms. Following these early effects, the facilitation effects persists into the N400 time-window suggesting facilitated semantic processing in both conditions, possibly linked to increased predictability of the upcoming picture name in the thematic condition as supported by the parietal distribution of this effect in the Laplacian analysis. Critically, in the case of taxonomic relationships, the Laplacian analysis also revealed a concurrent interference effect in the N400 window at a left frontal recording site. This effect likely reflects more effortful processing in lexical retrieval processes beginning after initial lexical activation (such as lexical selection) when placed in the context of taxonomically related words, leading to the engagement of left frontal cognitive control not seen in the thematic context. These results illustrate the importance of considering Laplacian transformation when studying the brain dynamics of language production using ERPs.

AUTHOR CONTRIBUTIONS
Elizabeth Jane Anderson: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; visualization; writing – original draft; writing – review and editing. **Katherine Midgley:** Conceptualization; funding acquisition; methodology; resources; software; supervision; validation; writing – review and editing. **Phillip Holcomb:** Conceptualization; funding acquisition; methodology; resources; software;

PSYCHOPHYSIOLOGY SPR

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ORCID

Elizabeth J. Anderson https://orcid.org/0000-0002-6344-5344
Stephanie K. Riès https://orcid.org/0000-0003-0308-0635

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SUPPORTING INFORMATION

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APPENDIX

TABLE A1 Full list of target images and prime words (taxonomic, thematic, taxonomic unrelated, and thematic unrelated) for each image

Target image (picture name)	Taxonomic prime (written word)	Thematic prime (written word)	Unrelated prime (taxonomic) (written word)	Unrelated prime (thematic) (written word)
acorn	pecan	squirrel	package	stamp
airplane	helicopter	pilot	pie	oven
angel	devil	halo	blender	bread
apple	pear	core	screw	hammer
arm	leg	sleeve	peas	husk
armor	suit	shield	sink	drain
arrow	dart	target	concrete	wall
baby	child	crib	crate	farm
bacon	sausage	eggs	vault	lock
ballerina	gymnast	tutu	rag	shampoo
balloon	kite	air	wasp	honey
banana	kiwi	monkey	torch	flame
basket	hamper	picnic	dentures	floss
bee	wasp	honey	kite	hole
beer	wine	keg	ship	anchor
boat	ship	anchor	pear	keg
bottle	jar	cork	mule	desert
box	crate	gift	child	crib
bracelet	necklace	wrist	tiger	roar
brick	concrete	wall	dart	target
bridge	road	river	elbow	glove
bus	train	driver	priest	convent
button	zipper	shirt	coral	ocean
cake	pie	oven	helicopter	pilot
camel	mule	desert	boot	laces
candle	torch	flame	plow	harvest
canoe	raft	oar	spoon	vine
car	truck	engine	ribbon	loom
castle	palace	moat	stool	desk
cat	leopard	meow	wheat	brake
chair	stool	desk	palace	moat
cherry	plum	blossom	leg	sleeve
church	mosque	altar	koala	bamboo
cliff	hill	rock	truck	engine
clock	watch	time	toe	ring
comb	brush	hair	hawk	night
corn	peas	husk	sailor	treasure
cracker	biscuit	salt	raft	saddle
crown	tiara	jewel	shark	hook
dragon	unicorn	fire	jar	cork
ear	chin	wax	hill	rock
elephant	zebra	tusk	knee	sandal

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TABLE A1 (Continued)

Target image (picture name)	Taxonomic prime (written word)	Thematic prime (written word)	Unrelated prime (taxonomic) (written word)	Unrelated prime (thematic) (written word)
envelope	package	stamp	pecan	squirrel
eye	nose	glasses	cushion	mattress
finger	toe	ring	wine	time
fireplace	chimney	soot	cabbage	dressing
fish	shark	hook	coat	neck
flask	jug	whiskey	stairs	rung
foot	knee	sandal	clam	pearl
frog	turtle	pond	toast	syrup
gate	fence	latch	mop	dirt
grapes	peach	vine	tiara	jewel
grass	lawn	weeds	necklace	wrist
hand	elbow	glove	road	river
hay	wheat	farm	leopard	meow
heart	lung	blood	tire	garden
horse	donkey	saddle	detergent	bubble
hose	sprinkler	garden	cabin	pole
house	cottage	garage	kiwi	air
knife	spoon	butcher	squash	seeds
ladder	stairs	rung	jug	whiskey
lettuce	cabbage	dressing	chimney	soot
lion	tiger	roar	ax	wood
map	globe	compass	brush	hair
mask	costume	face	dolphin	blubber
moon	sun	eclipse	cigar	smoke
moth	beetle	cocoon	hammock	rope
mouse	rat	cheese	pin	thread
nail	screw	hammer	hurricane	wind
needle	pin	thread	rat	cheese
nun	priest	convent	train	driver
owl	hawk	night	suit	shield
oyster	clam	pearl	purse	movie
panda	koala	bamboo	mosque	altar
pencil	crayon	eraser	radio	cable
penny	dime	copper	zipper	shirt
pillow	cushion	mattress	nose	glasses
pipe	cigar	smoke	sun	eclipse
pirate	sailor	treasure	zebra	tusk
pumpkin	squash	seeds	watch	butcher
rabbit	hamster	carrot	chin	wax
rose	tulip	thorn	glue	paper
safe	vault	lock	peach	oar
saw	ax	wood	plum	blossom
scarf	coat	neck	lawn	weeds

TABLE A1 (Continued)

Target image (picture name)	Taxonomic prime (written word)	Thematic prime (written word)	Unrelated prime (taxonomic) (written word)	Unrelated prime (thematic) (written word)
shell	coral	ocean	gymnast	tutu
shoe	boot	laces	hamster	carrot
shovel	rake	hole	door	curtain
soap	detergent	bubble	donkey	core
stapler	glue	paper	tulip	thorn
swing	hammock	rope	beetle	cocoon
teeth	dentures	floss	hamper	picnic
tent	cabin	pole	sprinkler	gift
theater	arena	movie	biscuit	salt
toaster	blender	bread	devil	halo
tornado	hurricane	wind	bell	referee
towel	rag	shampoo	dime	copper
tractor	plow	harvest	globe	compass
tree	bush	leaf	medal	winner
trophy	medal	winner	bush	leaf
tub	sink	drain	sausage	eggs
tv	radio	cable	crayon	eraser
vacuum	mop	dirt	fence	latch
waffle	toast	syrup	turtle	pond
wallet	purse	money	unicorn	fire
whale	dolphin	blubber	costume	face
wheel	tire	brake	lung	blood
whistle	bell	referee	cottage	money
window	door	curtain	rake	monkey
yarn	ribbon	loom	arena	garage

TABLE A2 Percentage of targets, taxonomic primes, and thematic primes that belong to each semantic category

Category	Target %	Taxonomic %	Thematic %
Non-living versus Living			
Living	29.09	30.00	12.73
Non-living	70.91	69.09	87.27
Non-manipulable versus Manipulable			
Manipulable	47.27	51.82	35.45
Non-manipulable	52.73	48.18	64.55
Semantic categories			
Activities and sports	10.00	10.00	5.45
Animal	8.18	8.18	2.73
Body part	7.27	7.27	4.55
Building and infrastructure	6.36	6.36	4.55
Clothing and accessories	5.45	9.09	10.91
Financial	2.73	1.82	1.82
Food and drink	11.82	11.82	10.00
Household items	15.45	14.55	9.09
Nature	7.27	6.36	22.73
Person	4.55	4.55	4.55
Tool	11.82	11.82	12.73
Transportation	6.36	5.45	2.73
Miscellaneous	2.73	2.73	8.18