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The primacy of taxonomic semantic organization over thematic semantic organization during picture naming

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ABSTRACT

Different organizational structures have been argued to underlie semantic knowledge about concepts; taxonomic organization, based on shared features, and thematic organization based on co-occurrence in common scenes and scenarios. The goal of the current study is to examine which of the two organizational systems are more engaged in the semantic context of a picture naming task. To address this question, we examined the representational structure underlying the semantic space in different picture naming tasks by applying representational similarity analysis (RSA) to electroencephalography (EEG) datasets. In a series of experiments, EEG signals were collected while participants named pictures under different semantic contexts. Study 1 reanalyzes existing data from semantic contexts directing attention to taxonomic organization and semantic contexts that are not biased towards either taxonomic or thematic organization. In Study 2 we keep the stimuli the same and vary semantic contexts to draw attention to either taxonomic or thematic organization. The RSA approach allows us to examine the pairwise similarity in scalp-recorded amplitude patterns at each time point following the onset of the picture and relate it to theoretical taxonomic and thematic measures derived from computational models of semantics. Across all tasks, the similarity structure of scalp-recorded neural activity correlated better with taxonomic than thematic measures, in time windows associated with semantic processing. Most strikingly, we found that the scalp-recorded patterns of neural activity between taxonomically related items were more similar to each other than the scalp-recorded patterns of neural activity for thematically related or unrelated items, even in tasks that makes thematic information more salient. These results suggest that the principle semantic organization of these concepts during picture naming is taxonomic, at least in the context of picture naming.

1. Introduction

In our everyday life, we encounter objects in a variety of contexts; apples might be seen in an orchard, a grocery store, or on the kitchen counter when preparing to bake a pie. In these different contexts, different aspects of our understanding of an apple, sometimes called our “semantic memory” or our “conceptual representation”, may be more or less relevant. Two distinct principles have been argued to be critical for organizing concepts in semantic space, either taxonomic or thematic structures (Mirman et al., 2017). Taxonomic structure is concerned with whether items share features, like both being animals, (e.g., dog-cat), while thematic structures are based on whether two items are likely to appear within the same events or scenarios (e.g., dog-bone). Both of these types of structures can help make sense of the world around us. Taxonomic relationships allow us to generalize the properties of known things to novel concepts. For example, if we know that apples and mangosteens are both fruits, we will be able to infer that mangosteens are edible even if we have never encountered that particular fruit before. Thematic relationships guide our expectations of what we are going to encounter in scenarios or events. For example, apples, knives, aprons, and pie tins share few physical features. However, they are thematically related to a kitchen setting, and one can expect to encounter all of them while baking a pie, which provides information that a pie tin might be expected if apples, knives, and aprons are observed. This kind of

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information complements taxonomic knowledge, but depending on the kind of knowledge that is necessary for a particular system, either taxonomic or thematic semantic information may be more or less relevant, and potentially more or less activated.

Much of the previous research looking at taxonomic and thematic structure has focused on whether they are dissociable semantic systems. A growing consensus is that these types of knowledge rely on distinct brain regions, the anterior temporal lobe (ATL) and temporoparietal cortex (TPC) (e.g., de Zubicaray et al., 2013; Geng and Schnur, 2016; Teige et al., 2019; Mirman and Graziano, 2012; Henseler et al., 2014; Rogers et al., 2004; Schwartz et al., 2011;Tsagkaridis et al., 2014; Kalénine and Buxbaum, 2016; Zhang et al., 2024). To account for these findings, Mirman et al. (2017) proposed a dual-hub hypothesis, arguing that each region serves as a hub for different kinds of semantic knowledge, with the ATL identified as the taxonomic hub and the TPC as the thematic hub. Under this view, these hubs are differentially engaged based on the requirements of different kinds of tasks: object identification and categorization rely more on taxonomic information and activity in ATL, while tasks that require associations, like word association tasks, rely more on thematic information and activity in the TPC. The Controlled Semantic Cognition (CSC) account describes a different role for the ATL and TPC. This account assumes a single hub for processing both taxonomic and thematic knowledge in the ATL region. The fact that TPC activation is observed for thematic processing is explained by assuming that the TPC is part of a broader semantic control system comprised of the inferior frontal gyrus (IFG) and posterior middle temporal gyrus (pMTG) (Jefferies et al., 2020; Lambon Ralph et al., 2017; Thompson et al., 2017; Whitney et al., 2011; Zhang et al., 2021), and that this control system is crucial for the retrieval of task-relevant information based on circumstances when non-dominant information must be retrieved (Davey et al., 2015; Davey et al., 2016; Demb et al., 1995; Noonan, Jefferies, Visser, & Lambon Ralph, 2013; Noppeney & Price, 2004; Wagner, Paré-Blagoev, Clark, & Poldrack, 2001; Whitney et al., 2011; Zhang et al., 2004). Thematic information is assumed to be non-dominant, and therefore when participants are asked to retrieve thematic information, additional semantic control is needed to draw attention to this non-dominant features information over the dominant, and activated, taxonomic information. While these two theories make different claims about the extent to which each of the two semantic systems are activated, these differences are largely empirically untested and the status of the nondominant semantic system is largely unknown.

The current research attempts to fill this gap by looking at the extent to which two types of semantic systems are engaged during picture naming and whether the level of engagement is influenced by the semantic context of the task. Previous studies using picture naming tasks have demonstrated that both taxonomically and thematically related concepts are co-activated, indicating that both organizational principles in semantic space are accessible in picture naming. Models of language production agree that during retrieval of the name of the picture, the target word and its semantically related neighbors will receive activation. Previous studies involving picture naming have shown that both types of semantic representations are co-activated when producing the name of the objects (e.g., de Zubicaray et al., 2013; Howard et al., 2006; Rose & Rahman, 2016). For example, in the picture-word interference paradigm (PWI), the presentation of both taxonomically and thematically related distractor words has been shown to influence the speed with which a target picture is named. The results with taxonomically-related distractor words are clear and robust, with these distractors slowing the speed with which a target picture is named, relative to a condition with a superimposed unrelated distractor word. The thematically related distractor words have been shown to have a null effect (Lupker, 1979) or to facilitate picture naming (Abdel Rahman & Melinger, 2007; Alario et al., 2000; Costa et al., 2005; Damian and Spalek, 2014; de Zubicaray et al., 2013; La Heij et al., 1990; Sailor et al., 2009).

Similarly, evidence for both taxonomic and thematic organization of knowledge in picture naming has come from the blocked cyclic naming paradigm (e.g., Damian et al., 2001). In this task, participants repeatedly name pictures of small sets of objects, and the context in which objects are presented influences the naming speed. Pictures are arranged so that objects are exemplars of the same category within the homogeneous block, whereas objects are from different categories in heterogeneous blocks. Most previous studies have used taxonomic categories to define the homogeneous block, for example, a block of pictures of types of furniture. As with PWI, a semantic interference effect is typically observed in this paradigm with taxonomic relationships: the same pictures are named slower when they appear in taxonomically homogeneous blocks than when they appear in taxonomically heterogeneous blocks (e.g., Belke et al., 2005; Damian et al., 2001; Harvey and Schnur, 2016; Schnur et al., 2006). Having the homogeneous block be defined by theme, yields more mixed results. Abdel Rahman & Melinger (2007) reported an interference effect for the thematically defined homogeneous block when the topic of the thematic context was not explicitly provided. However, when the objects were not obviously related to one another, as in their later study (Abdel Rahman and Melinger, 2011), the interference effect only emerged when the topic cues served to bind the objects together into a meaningful context. Other studies without this explicit theme cueing have failed to find any impact of thematically-defined homogeneous categories compared to the heterogeneous condition (de Zubicaray et al., 2014), and still, other studies have reported a faciliatory effect of thematic categories (e.g., McDonagh et al., 2020). What the effects of thematic relations in different contexts are and why taxonomic and thematic relations produce different effects in picture-word interference and blocked cyclic naming tasks remains a topic of debate. But the discovery of reaction time effects in picture naming tasks involving both taxonomic and thematic relations has led at least some theorists to argue that both systems play some role in picture naming, along with other tasks that rely on semantic processing (Mirman et al., 2017). There are some challenges to drawing these conclusions from reaction time data alone, as reaction time reflects the end of a chain of complex processes. Concerns have been raised that some of the effects observed in the PWI paradigm (e.g. Janssen et al., 2008) and the blocked cyclic naming paradigm (e.g. Belke, 2017) have to do with factors other than lexical-semantic processing, and the cognitive level at which these effects occur are difficult to capture solely from reaction time.

Another strong line of evidence comes from dissociations between individuals with aphasia in the kinds of naming errors they produce following a stroke. For example, Schwartz et al. (2011) investigated the semantic errors made by patients with language deficits following a left-hemisphere stroke in picture naming.[1] In their cohort, voxel-based lesion-symptom mapping revealed that error patterns that reflect taxonomic structure (e.g., calling a picture of an apple “pear”) were associated with damage to the left ATL and errors that reflect thematic structure (e.g., responding “worm” to a picture of an apple) were associated with damage to the left TPC. The distinct types of errors made by patients suggested that taxonomic and thematic knowledge are two distinct types of semantic relations that are essential for naming objects, subserved by distinct neural substrates. However, it is also the case that thematic errors were rare in this population, with only 2 of 55 participants making more thematic errors than taxonomic errors, and both of those participants showing low overall semantic error rate, suggesting that taxonomic organization may play a more central role in this task.

Still, the results from these different empirical approaches to picture naming has been interpreted as evidence for theories that assume taxonomic and thematic knowledge of objects are two distinct semantic

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[1] It is worth noting that Blackett et al. (2022) reported that thematic associations in the context of language are supported by a distributed network linking temporal pole and inferior temporal regions to more posterior and peri-Sylvian structures, as opposed to discrete cortical areas, using connectome-based lesion-symptom mapping.

systems that are engaged when we name pictures. Although there is still controversy regarding how the two types of semantic relations impact lexicon selection, there is a general consensus that both taxonomically and thematically related concepts are at least co-activated with the target word, meaning that both ways of organizing objects in semantic space are accessible during picture naming. However, the extent to which both kinds of semantic knowledge are accessed during picture naming remains an open question.

1.1. The present research

The current research aims to examine investigate the extent to which both kinds of conceptual representation are activated during picture naming, and whether the type of conceptual representations that are accessed is influenced by the semantic context of the task, with a series of studies that rely on electroencephalography (EEG) methods. For Study 1, two existing picture naming datasets were re-analyzed by applying representational similarity analysis (RSA, Kriegeskorte et al., 2008) to EEG datasets to probe semantic spaces in picture naming tasks; the first is from a taxonomic blocked cyclic naming paradigm and the second from a picture naming experiment with no inherent structure in the order of pictures. In Study 2, RSA was applied to the data from a new EEG experiment that employed the blocked cyclic naming paradigm to generate either taxonomic or thematic contexts using the same items. Study 2 aimed to examine whether taxonomic or thematic systems are more engaged in picture naming when tasks direct participants attention to thematic categories, and whether semantic context can change the way concepts are organized in mental lexicon.

1.2. EEG-RSA approach

Our measure for whether taxonomic and thematic semantic systems are engaged in these different picturing naming task contexts relies on applying an analytical approach, RSA, to a series of EEG datasets. This method allows us to calculate the whole-scalp neural similarity in response to different stimuli and look at how this neural similarity is related to measures of taxonomic and thematic relatedness. RSA is a type of multivariate pattern analysis (MVPA) based on the assumption that a stimulus activates a population of neuronal units in a distributed manner (Kriegeskorte et al., 2008). A pair of stimuli that are similar in representation will also have a similar pattern of neural activity. When applying this logic to EEG data, a pair of stimuli similar in representation should have similar event-related potential (ERP) vectors with each index of the vector reflecting a channel being recorded at the scalp, therefore connecting the scalp-recorded ERP vectors with computational models allows us to examine the type of information being represented in different time windows. For example, we estimate the pattern across the whole scalp over time while naming individual pictures, like the pattern in response to a picture of a DOG, a picture of a CAT, and a picture of a BONE. We can then calculate the pairwise similarity of these different whole-scalp patterns, the similarity of DOG to CAT, DOG to BONE, and CAT to BONE. Several recent studies have shown the effectiveness of applying RSA to EEG data to answer questions about processing conceptual information from words and pictures (e.g., Wang et al., 2020; He et al., 2022; Hubbard and Federmeier, 2021; Grootswagers et al., 2017).

The logic of RSA makes it an ideal tool to study the engagement of taxonomic and thematic systems in picture naming. We can construct representational similarity spaces based on taxonomic and thematic theories by building the theoretical models that best capture the taxonomic or thematic relations between the same set of objects. By correlating the similarity structure of the EEG data and the taxonomic/thematic theoretical models, one can investigate what kind of semantic space is being used during different picture naming tasks. Returning to the example above, we can calculate across multiple time points whether the whole scalp pattern for DOG is more similar to CAT, as would be expected by a taxonomic theory, or more similar to BONE, as would be expected by a thematic theory. If the engagement of taxonomic and thematic semantic systems is influenced by task context, then we would predict that task contexts that bias towards thematic knowledge should result in higher similarity between DOG and BONE, and task contexts that bias towards taxonomic knowledge should result in a higher similarity between DOG and CAT.

The example above oversimplifies the approach to some extent. Taxonomic and thematic similarity can be treated as continuous measures of similarity, rather than categorical – related or not related. To take advantage of a continuous similarity scale, we relied on computational measures to construct theoretical similarity matrices for taxonomic and thematic similarity. Specifically, the taxonomic theoretical similarity matrix was derived based on Wu-Palmer semantic similarity values (Wu and Palmer, 1994). The Wu-Palmer similarity is a measure derived from WordNet, a large lexical database that groups word senses into hierarchical taxonomic categories. The Wu-Palmer similarity calculates the semantic relatedness by considering the depth of the two word senses in the WordNet taxonomies, together with the depth of their Least Common Subsumer (LCS), that is, the most specific ancestor node of the two word senses. For example, for objects “cherry” and “persimmon”, their LCS is “edible fruit”. Due to the lack of consistency in the thematic measures used in past literature, two thematic measures were examined: Latent Semantic Analysis (LSA, Landauer and Dumais, 1997) and Pointwise Mutual Information (PMI). In LSA, information about the frequency of occurrence of words in documents is extracted from texts. Words are considered semantically similar to the extent that commonly appear in similar documents. LSA has been used as a thematic model capturing the relations between a pair of words as induced by the language contexts, assuming that words have similar meanings if they tend to occur in similar contexts. PMI is another thematic measure that has been used in previous studies (e.g., McDonagh et al., 2020), which indexes the probability that two words co-occur in text, with PMI $=$ 0 indexing co-occurrence at chance level, and positive and negative values indexing more and less than chance level. The PMI for each item pair was calculated using the Palmetto toolbox (Röder et al., 2015). Zhai (2022) provided evidence supporting the use of LSA and PMI as thematic measures, as they were assessed with the subjective ratings of 659 word pairs in Landrigan and Mirman (2016) and results showed that LSA and PMI moderately correlate with the subjective judgments of thematic relatedness but not with the taxonomic relatedness. Correlating the theoretical models of taxonomic and thematic organization with the EEG enables us to determine whether the neural activity is related to the taxonomic model (Wu-Palmer) to the thematic model (LSA or PMI), or both, and determine whether the task context changes the extent to which each kind of representational similarity space is used for the task.

To calculate this correlation between electrophysiological response and theory, an ERP waveform for each stimulus is derived at each scalp-recorded channel. At each time point, the neural activity pattern associated with each stimulus is represented by a vector of amplitudes across the whole scalp. For each subject and at each time point after the onset of the stimulus, a similarity structure – based on the correlation of the vector of amplitudes across the whole scalp for each stimulus to every other stimulus – is constructed and correlated with each of the theoretical measures of semantics. This process is repeated for each time point and averaged across subjects to derive a time series of averaged similarity values that measures how similar the EEG-derived brain activity and theoretical models are at each time point after a stimulus is shown. This analysis can be done for each theoretical semantic model and each task to compare the extent to which the brain activity correlates with different types of semantic information under different task contexts. A schematic illustration of the EEG-RSA analyses is shown in Fig. 1.

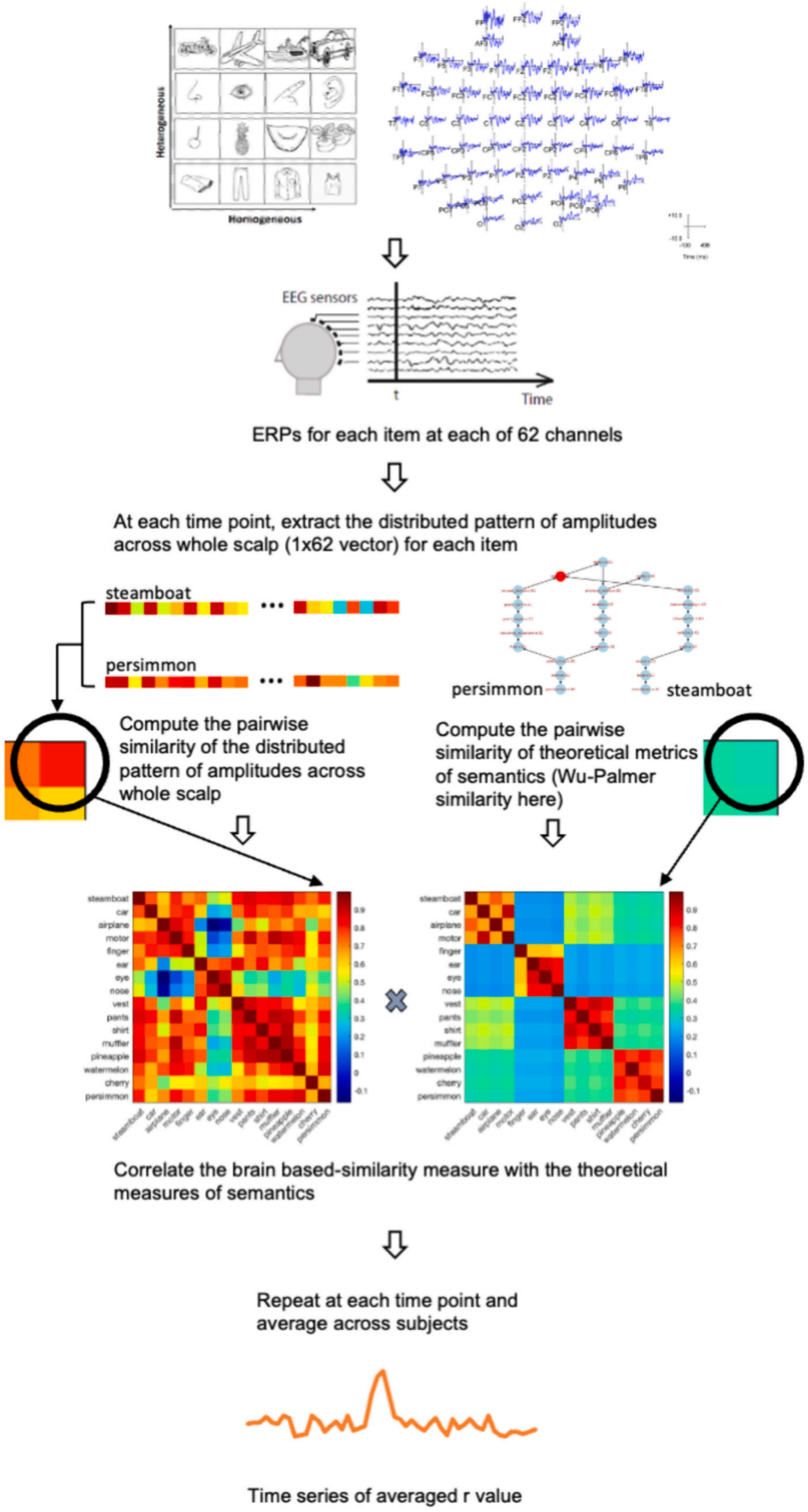

Fig. 1. The schematic illustration of applying the theory-based RSA to EEG datasets.

1.3. Predictions

If semantic organization relies on taxonomic knowledge in picture naming, the EEG-based similarity structure will correlate more strongly with the taxonomic model (Wu-Palmer similarity) than with thematic models (LSA/PMI). Conversely, the EEG-based similarity structure will correlate more strongly with thematic models (LSA/PMI) than with the taxonomic model (Wu-Palmer similarity). If the engagement of taxonomic and thematic semantic systems is influenced by task context, we predict that the semantic context will affect the extent to which brain activity patterns align with theoretical semantic models (taxonomic vs. thematic). Specifically, if the task context favors taxonomic organization, the EEG-based similarity structure will correlate more strongly with the taxonomic model (Wu-Palmer similarity) than with thematic models (LSA/PMI). Alternatively, when the task context favors thematic organization, the EEG-based similarity structure will align more closely with thematic models (LSA/PMI) than with the taxonomic model (Wu-Palmer similarity).

2. Study 1

For Study 1, we re-analyzed two existing picture naming datasets collected in Dr. Qingqing Qu's lab at The Institute of Psychology, Chinese Academy of Science, with RSA to probe semantic spaces in picture naming tasks. Dataset 1 is a blocked cyclic naming study in which participants named objects in a taxonomically homogeneous or heterogeneous block. Dataset 2 is a picture naming study with no specific task structure that draws participants' attention to objects' taxonomic or thematic information.

3. Dataset 1

3.1. Methods

Dataset 1 is a previously published study (Feng et al., 2021). The methods were described fully in that paper but reiterated here.

3.1.1. Participants

Twenty-four native Mandarin Chinese speakers (17 females, mean age of 22 years) participated and were compensated for their time. All participants were right-handed, with normal or corrected-to-normal vision and no history of language disorders.

3.1.2. Materials and design

Sixteen objects were selected from four taxonomic categories and were arranged in a 4 × 4 matrix so that items in rows formed semantic homogeneous blocks whereas items in columns formed semantic heterogeneous blocks. Eight blocks (four homogeneous and four heterogeneous) were presented in an alternating sequence. The order of the four blocks was determined by a Latin Square design. Within each block, each item was presented for four cycles, resulting in 16 trials, in a pseudorandom order such that items were never repeated on adjacent trials. Therefore, for each participant, the testing session for semantic blocks included 128 trials (16 trials in each of 8 blocks).

3.1.3. Procedure

The experiment was run using *E*-prime, with a microphone recording vocal responses. Participants were tested individually and were asked to name objects as fast and accurately as possible. In each block, participants were first asked to familiarize themselves with the four objects, with the corresponding names printed underneath each object. Each trial started with a fixation (500 ms) and then a blank screen (500 ms), followed by an object (2000 ms) in the center of the screen against a white background. The inter-trial interval was 1000 ms. Participants received a practice block consisting of four filler objects, followed by the experimental blocks. The entire experiment lasted for approximately 90 min.

3.1.4. EEG recordings and pre-processing

EEG signals were recorded with 64 electrodes secured in an elastic cap (Electro Cap International) using Neuroscan 4.3. The vertical electrooculogram (VEOG) was monitored with electrodes placed above and below the left eye. The horizontal EOG (HEOG) was recorded by a bipolar montage using two electrodes placed on the right and left external cantus. The left mastoid electrode served as a reference. All electrode impedances were below 5 kΩ. Electrophysiological signals were amplified with a band-pass filter of 0.05 and 70 Hz (sampling rate 500 Hz). The EEGLAB toolbox based on MATLAB was used for the following procedure of preprocessing EEG signals: offline filter with a high-pass cutoff of 0.1 Hz and a low-pass cutoff of 30 Hz, removal of an ocular artifact using independent component analyses (ICA) analysis on segmented data (−800 to 1500 ms relative to the picture onset), manual rejection of epochs with extensive fluctuation and signals below/above ±70 μV, offline re-referencing against the average reference. The EEG was segmented into 600 ms epochs relative to picture onset that included a 100 ms pre-stimulus baseline and a 500 ms post-stimulus interval.

3.2. Data analysis

Data with missing recordings (1.5 %), incorrect responses (0.6 %), latencies shorter than 300 ms or longer than 1500 ms (3.5 %), and beyond 2.5 SDs (1.0 %) were excluded from the following analyses. For the EEG data analysis, a further 3.0 % of trials were excluded due to artifacts. On average, 57 artifact-free trials in the homogeneous condition and 59 trials in the heterogeneous condition were entered into EEG data analysis.

3.2.1. Theory-based RSA

The theoretical similarity values for all possible pairs formed by the 16 items were calculated based on the taxonomic (Wu-Palmer similarity) and thematic (LSA, PMI) theoretical models. The theoretical similarity values derived from each model constitute a 16 × 16 matrix. The correlations between the matrices from Wu-Palmer and LSA, Wu-Palmer and PMI, and LSA and PMI are 0.34, 0.35, and 0.44, respectively. For each participant, the neural representation of each item is characterized by a 16 × 16 matrix at each time point. Each element of the matrix measures the pairwise similarity between item-specific EEG vectors. The Spearman's rank correlation, a non-parametric measure, was calculated between the neural similarity matrix and each of the theoretical similarity matric at each time point for each participant. Spearman's correlation was used to allay concerns that the distributions being evaluated may be non-Gaussian. In this way, we obtained time series of correlations for each theoretical model. For statistical analysis, firstly, a cluster-based permutation test (Maris and Oostenveld, 2007) was used to determine the significance of the differences between the time series associated with each theoretical model. Secondly, since previous studies have identified the time window between 180 ms and 300 ms as crucial for semantic processing (e.g., Feng et al., 2021), we conducted another analysis to examine the theory-based RSA results within this time window. The item-specific EEG vectors were averaged across the time points across the time points within this time window and then used to construct the neural similarity matrix. The correlations between the resulting neural matrix and each of the theoretical matrices (Wu-Palmer, LSA, and PMI) were then computed and transformed using Fisher-z transformation. Then the transformed correlation values for the taxonomic model and each thematic theoretical model were compared by ANOVA.

3.3. Results

3.3.1. Behavioral results

The picture naming latencies are shown in Fig. 2. The response times in the taxonomically homogeneous blocks were longer than in the heterogeneous blocks (562 vs. 525 ms). A linear mixed-effects model analysis (Baayen et al., 2008) was conducted using R package lme4 (Bates and Maechler, 2009). The model included the main effects of block and cycle, as well as their interaction, was constructed, with a full random structure implemented. The results showed a significant main effect of block ($\beta = 37.11$, SE $= 7.56$, $t = 4.91$, $p < .001$), suggesting that it took participants longer to name pictures when they were presented in a taxonomically homogeneous context. The block effect interacted with cycles ($\beta = 20.57$, SE $= 10.12$, $t = 2.03$, $p = .042$).

3.3.2. Theory-based RSA

We calculated the time courses of averaged correlation values between neural similarity patterns and three theoretical matrices and subtracted the mean correlation values within −100–0 ms from the time series of averaged correlation values. The baseline corrected time series for the taxonomic model (Wu-Palmer) and each thematic model (LSA and PMI) are plotted in Fig. 3A. A cluster-based permutation test confirmed that EEG-based similarity structure correlates better with what was predicted by Wu-Palmer similarity than that of LSA ($ps < 0.033$) or PMI ($p < .001$). The results of ANOVA implies a significant effect of theoretical model within the time window of semantic processing ($F(2,46) = 13.73$, $p < .001$). The post-hoc comparisons shows that neural activity within the time window associated with semantic processing correlates better with Wu-Palmer similarity matrix compared to LSA ($p < .001$) or PMI ($p < .001$) (see Fig. 3B).

The theory-based RSA demonstrated that the neural activity patterns during picture naming correlate better with taxonomic models than thematic ones, indicating that objects were organized into taxonomic categories in the semantic space during this task. Since the objects were taxonomically related to each other, the context of the blocked cyclic naming task might require the participants to attend more to the taxonomy of objects and change the organization of word meaning temporarily, moving towards the taxonomic end. Another dataset without such a task structure was examined in the following section.

4. Dataset 2

Dataset 2 is an unpublished dataset collected by Qu lab. In this study, all participants were required to name a set of pictures. It is worth noting that there are several important experimental differences between Dataset 1 and Dataset 2. In blocked cyclic naming, the same set of pictures is presented multiple times, which allows for statistically robust ERPs to be calculated for each individual participant's response to each individual picture. In contrast, in Dataset 2, each participant named each picture only once, meaning that each individual contributed at most a single EEG waveform for each picture. Given the noisiness of the data, it is to be expected that the correlation levels observed with Dataset 2 should be lower than those observed in Dataset 1.

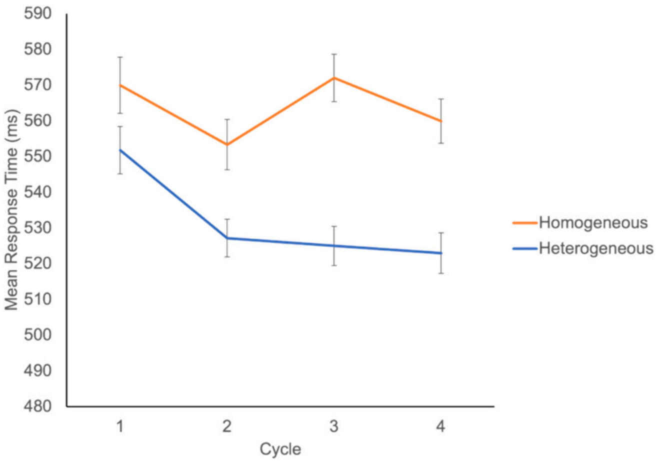

Fig. 2. Average naming latencies for taxonomically homogeneous vs. heterogeneous blocks in Study 1 dataset 1. Error bars indicate the standard error of the mean.

4.1. Methods

4.1.1. Participants

Thirty native Mandarin Chinese speakers participated and were compensated for their time. All participants were right-handed, with normal or corrected-to-normal vision and no history of language disorders. Participants gave informed consent, and the study was approved by the Institutional Review Board (IRB) of the Institute of Psychology, Chinese Academy of Sciences.

4.1.2. Procedure

All participants were required to name a set of pictures. Before the experiment, participants were asked to be familiar with the pictures and their corresponding names through a learning phase. The 120 target pictures were presented in random order. They were split into three lists. Each had 40 target pictures, preceded by the three warming-up items. Therefore, each participant completed 258 trials in total. A short break was given between two consecutive lists. In the spoken picture naming task, each trial started with a fixation (500 ms) and then a blank screen (500 ms), followed by a target picture in the center of the screen against a white background. The target picture disappeared once the participants initiated a detected response or after a time out of 4000 ms. The interval between two successive trials is 1000 ms. Participants were asked to speak aloud the name corresponding to the presented picture as rapidly and accurately as possible.

4.2. EEG recordings and pre-processing

The same EEG Recording devices and the same preprocessing protocols were used for Dataset 2 as in Dataset 1.

4.3. Data analysis

Data with a missing recording (0.92 %), incorrect responses (4.21 %), latencies shorter than 500 ms or longer than 3000 ms (1.38 %), and beyond 3 SDs (1.85 %) were excluded from the analysis. For EEG data, contaminated epochs (10.88 %) were further rejected. The same theory-based RSA methods used for analyzing Dataset 1 were applied to Dataset 2. The correlations between the similarity values from Wu-Palmer and LSA, Wu-Palmer and PMI, and LSA and PMI are 0.15, 0.33, and 0.45, respectively.

4.4. Results

4.4.1. Behavioral results

On average it took the participants 907 ms ($SD = 237$ ms) to orally name a picture of an object, which is shorter than the grand mean of naming latency (1044 ms) of timed norms for 435 object line drawings in Mandarin Chinese reported by Liu et al. (2011) and the results from Weekes et al. (2007) (1025 ms).

4.4.2. Theory-based RSA

The baseline corrected time courses of averaged correlation values between neural similarity patterns and the taxonomic model (Wu-Palmer) and thematic models (LSA and PMI) are plotted in Fig. 4A. The cluster-based permutation test showed that the correlation between

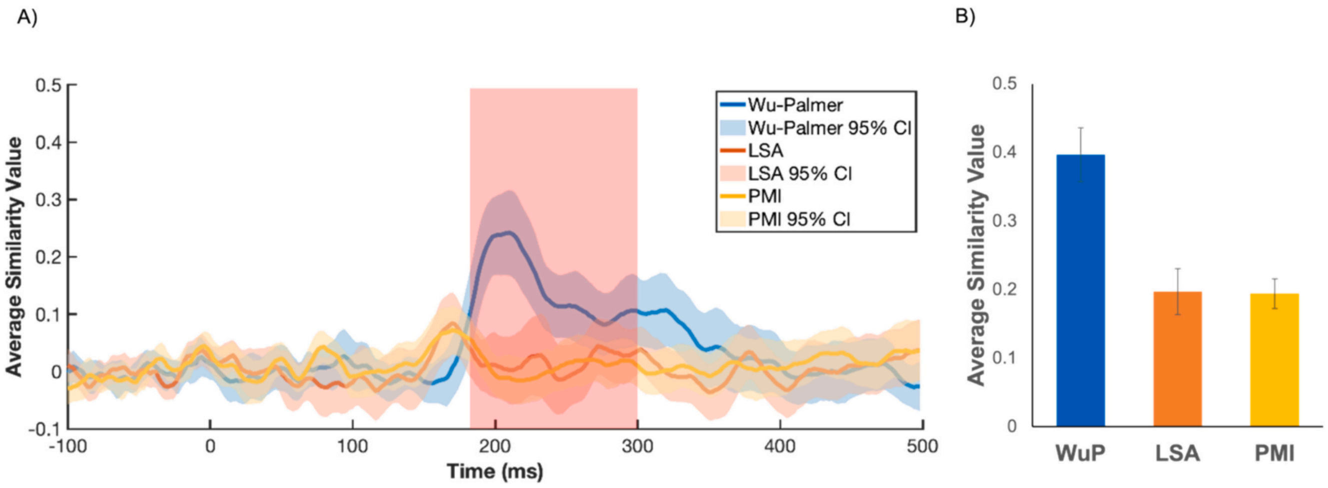

Fig. 3. (A) Baseline corrected time series of average similarity value between EEG-based similarity matrix and theoretical semantic matrices (Wu-Palmer similarity, LSA, and PMI) for the taxonomic blocked cyclic naming dataset (Study 1, dataset 1). Time window of 180–300 ms are highlighted. (B) Time window analysis of the taxonomic blocked cyclic naming study (Study 1 Dataset 1). Error bars indicate the standard error of the mean.

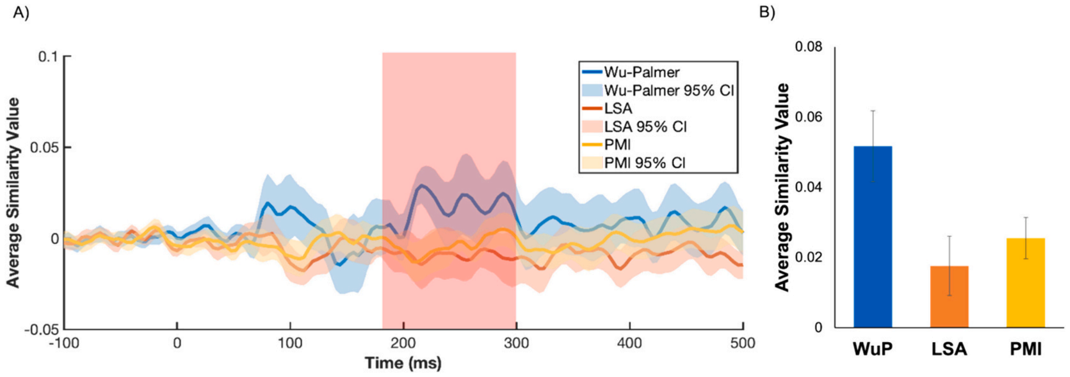

Fig. 4. (A) Baseline corrected time series of average similarity value between EEG-based similarity matrix and theoretical semantic matrices (Wu-Palmer similarity, LSA, and PMI) for the spoken picture naming dataset (Study 1 Dataset 2). Time window of 180–300 ms are highlighted. (B) Time window analysis of the spoken picture naming dataset (Study 1 Dataset 2). Error bars indicate the standard error of the mean.

neural activity and Wu-Palmer similarity is higher than that with LSA (ps < 0.048), and higher than that with PMI ($p = .023$). The theory-based RSA demonstrated that the EEG-derived similarity structure correlates better with the one predicted by taxonomic similarity than with thematic similarity. The results of ANOVA indicates a significant effect of model during the time window of semantic processing ($F(2,58) = 4.28$, $p = .018$) (see Fig. 4B), suggesting that neural activity pattern correlates better with Wu-Palmer similarity compared to LSA ($p = .031$) or PMI ($p = .047$).

4.5. Discussion

Study 1 examined the extent to which two types of semantic systems were engaged in picture naming by looking at two existing EEG datasets. The results of Dataset 1 might be explained by the semantic context of the taxonomic blocked cyclic naming paradigm. When the pictures of objects were presented in taxonomically related blocks, the participants' attention was directed to the taxonomic categories of the objects. The nature of the task might bias the results towards the taxonomic relations between concepts. However, such an explanation is less likely with Dataset 2. The theory-based RSA results consistently show that in picture naming studies with or without a task structure that directed participants to the taxonomic categories of the stimuli, the pairwise similarity of the item-specific EEG neural activity correlates better with the predicted similarity based on the Wu-Palmer measure, compared with that of LSA or PMI, indicating that picture naming, at least in these tasks, relies more on taxonomic knowledge than thematic knowledge.

5. Study 2

To gain deeper insight into the semantic space underlying picture naming, a critical question arises: Are concepts still organized taxonomically in the mental lexicon when the task context makes thematic categories of objects more salient? Study 2 test this question with a new EEG study in which two groups of individuals each complete a blocked cyclic naming study, with identical materials, with the difference between the groups being that for one group, the homogeneous block includes items that are taxonomically related, and for the other group the homogeneous block includes items that are thematically related. The blocked cyclic naming paradigm allows us to manipulate the semantic contexts in which objects appear, making it the ideal task for investigating context effects on the two types of semantic systems. By choosing the appropriate sets of objects, one can construct taxonomic and thematic contexts for the same items. We investigated whether the organization of word meanings can be temporarily biased towards taxonomic or thematic ends by explicitly manipulating the participants' attention to these two types of semantic information of the objects. This was examined through the category effect and theory-based RSA results across the two groups.

5.1. Methods

5.1.1. Participants

Thirty-two native Chinese speakers were recruited to participate in this experiment. They are undergraduate students from universities in Beijing, China. They were compensated for their participation at a rate of 60 RMB/h (about 10 USD/h). All participants have normal or corrected-to-normal vision.

5.1.2. Materials and design

A stimulus set of 16 objects was selected from 59 objects that fall within 6 taxonomies (professions, food, animal, tools, clothes, locations) and 8 themes (farm, forest, ocean, kitchen, restaurant, laboratory, wedding, Christmas) so that, within one block of trials, the items could be presented either with other members of the same taxonomic category (e.g., animal) or with thematically related members of the same context (e.g., farm). The related items do not share any phonological and orthographic information. The heterogeneous blocks are composed of four unrelated members from each category and context (e.g., farmer, deer, knife, and white coat). Each object is assigned to a heterogeneous block. Three online surveys were conducted to assess the taxonomic, thematic, and general semantic relatedness of all word pairs formed by the words in taxonomically related, thematically related, and unrelated blocks for all candidate stimuli sets. Each survey collected rating scores from different sets of 15 participants. The first rating asked participants to judge the taxonomic relatedness between word pairs, i.e., the degree of being in the same taxonomic category. The second rating asked participants to judge the thematic relatedness between word pairs, i.e., the degree of association via events or scenarios. The third rating asked subjects to judge the general semantic relatedness between word pairs. All three ratings were based on a 7-point scale (1 = not related at all, 7 = strongly related). The instructions for the relatedness ratings were adapted from Jones and Golonka (2012). Examples of taxonomically/thematically related word pairs were provided for the participants. For general relatedness, the thematically related pairs (M = 4.59, SD = 1.83) scored higher than the taxonomically related pairs (M = 3.75, SD = 1.22; *p* = .011), followed by unrelated pairs (M = 1.95, SD = 0.95; *p* < .001); In terms of taxonomic relatedness, taxonomically related pairs (M = 3.74, SD = 0.76) scored higher than the thematically related pairs (M = 3.36, SD = 0.64; p < .001), followed by unrelated pairs (M = 2.36, SD = 0.76; p < .001); For thematic relatedness, thematically related pairs (M = 4.15, SD = 1. 53) scored higher than the taxonomically related pairs (M = 2.08, SD = 0.52; p < .001) and unrelated pairs (M = 2.06, SD = 0.66; p < .001).

The line drawings were selected from Liu et al. (2011), Severens, Van Lommel, Ratinckx, & Hartsuiker (2005), and Google Images. Some pictures were edited to minimize the within-block visual similarity. All pictures are adjusted to the same size of 800 × 600 pixels and have a visual angle of approximately 5.7 (Fig. 5). To control for confounds related to visual similarity between different contexts, we calculated image similarities using multiple metrics, including mean squared error, root mean squared error, peak signal-to-noise Ratio, structural similarity index, visual information fidelity, and the Haar wavelet-based perceptual similarity index between object pairs (Reisenhofer et al., 2018). Our analysis revealed no significant differences across all image similarity metrics between conditions (all ps > 0.1).

Each participant was randomly assigned to one of the two subject groups: 1) taxonomic group or 2) thematic group. The taxonomic group only named items in the taxonomically homogeneous and heterogeneous conditions; the thematic group was only exposed to thematically homogeneous and heterogeneous conditions. The order of the experimental conditions (taxonomically/thematically homogeneous and heterogeneous) was counterbalanced between each group of subjects. The order of the four blocks within each experimental condition (e.g., professions, animals, tools, and clothes in taxonomically homogeneous conditions) was also counterbalanced across participants according to a Latin Square design. Within each block, the order of picture presentation was counterbalanced using Mix software (van Casteren and Davis,

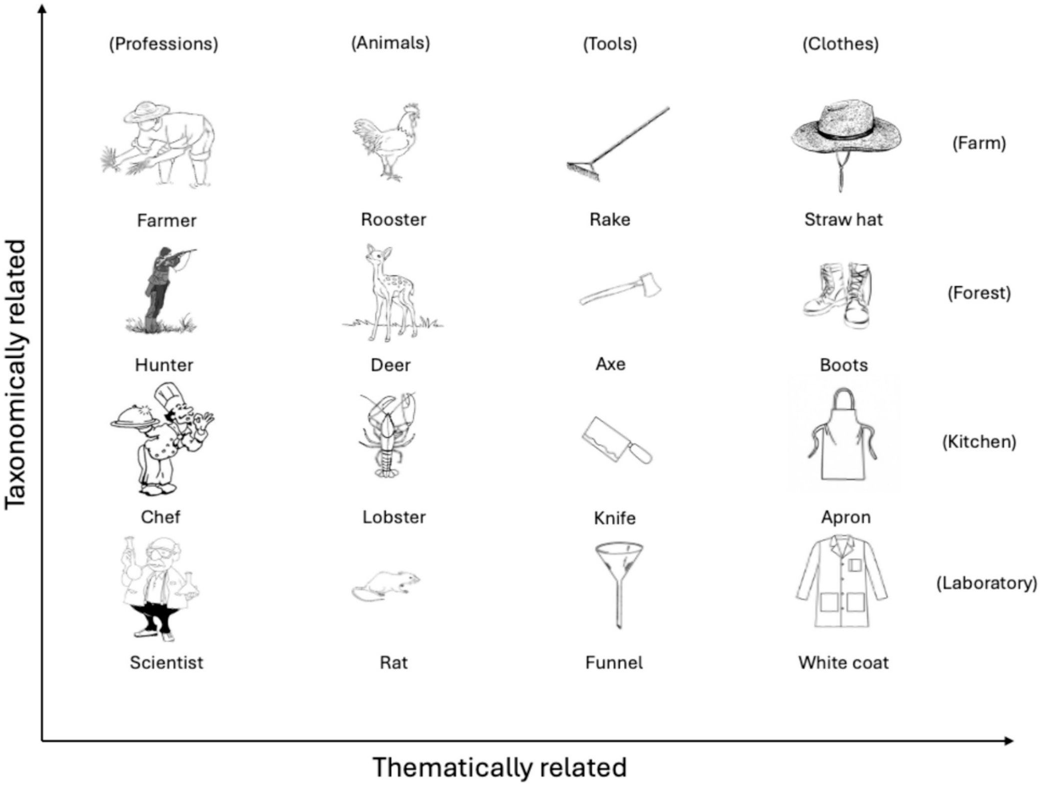

Fig. 5. Illustration of line drawings of the 16 objects for Study 2.

2006). Each block of four items was presented in pseudo-randomized order for four cycles (16 trials), requiring that no item appeared in consecutive trials. Each list, therefore, consisted of 128 trials.

5.1.3. Procedure

Participants were instructed to name the pictures as quickly and accurately as possible. Prior to the presentation of each block, participants were first familiarized with the pictures of the four objects with their names printed below. During the process of learning the names of pictures, for the taxonomic group, four objects belonging to each taxonomic category were shown on the same frame. In contrast, for the thematic group, four objects belonging to each theme were shown on the same slide. Erroneous naming responses were corrected. The trial presentation involved the following sequence: A fixation cross (+) was shown for 500 ms, followed by a blank screen for 500 ms and an object for 2000 ms at the center of the screen against a white background. The intertrial interval was 1000 ms. Participants received a practice block of four filler objects before naming the objects in the experimental blocks.

5.2. Data analysis

Data with missing recordings (0.95 %), incorrect responses (0.15 %), latencies shorter than 300 ms or longer than 1800 ms (1.00 %), and beyond 3 SDs (0.46 %) were excluded from the behavioral analyses.

5.2.1. Category effect

Since the same stimulus set was grouped into either taxonomically related blocks or thematically related blocks, the stimuli could be categorized into three types of item pairs: taxonomically related, thematically related, and unrelated. This design allows us to explore the semantic space under two different task contexts—taxonomic and thematic—by examining the category effect. By comparing the pairwise similarity in neural activity patterns for these three categories, we can determine whether semantic organization remains based on taxonomic knowledge even within a thematic task context. If the semantic space under a certain task context is organized according to taxonomic information, we should observe a higher pairwise similarity within taxonomically related pairs compared to thematically related or unrelated ones. Conversely, if objects are organized according to their thematic information in the semantic space, we should observe a higher pairwise similarity within thematically related pairs compared to taxonomically related and unrelated pairs.

For each participant, the item-specific EEG vector for each item across all 62 channels was computed by averaging the data of 8 presentations. At each time point, we computed the similarity between the neural activity pattern of all possible pairs formed by items from each of the three categories, i.e., taxonomically related (24 pairs, e.g., 农民, /nong2min2/, “farmer” and 猎人, /lie4ren2/, “hunter”), thematically related (24 pairs, e.g., 农民, /nong2min2/, “farmer” and 公鸡, /gong1ji1/, “rooster”), and unrelated pairs (72 pairs, e.g., 农民, /nong2min2/, “farmer” and, 漏斗, /lou4dou3/, “funnel”), by calculating the Pearson’s r value between the item-specific EEG vectors. The r values of each of the three categories were averaged at each time point. Whether and when there was a significant difference in the similarity of neural activity of taxonomically or thematically related pairs versus unrelated pairs was tested by a nonparametric clustered-based permutation procedure to correct for multiple comparisons across time points.

5.2.2. Theory-based RSA

In each task, the same theory-based RSA methods used for analyzing the two datasets in Study 1 were applied to Study 2. The correlations between the theoretical matrices were calculated (Wu-Palmer vs. LSA: 0.15, Wu-Palmer vs. PMI: 0.33; LSA vs. PMI: 0.45).

5.3. Results

5.3.1. Behavioral results

The picture naming latencies for the taxonomic and thematic tasks are shown in Fig. 6. A linear mixed-effects model analysis (Baayen et al., 2008) was conducted using the R package lme4 (Bates and Maechler, 2009). For the comparison between heterogeneous blocks of the two types of semantic relations, results showed only effects of the cycle (all ps < 0.05). Neither the main effect of semantic context ($\beta = -12.39$, SE $= 28.21$, $t = -0.44$, $p = .661$) nor the interaction between semantic context and cycle (all ps > 0.29) reached significance, suggesting that naming latencies of heterogeneous blocks of the two semantic relation type were equivalent to serve as comparable baselines.

For both types of semantic relatedness, responses to pictures presented in the homogeneous blocks were longer than those in the heterogeneous blocks, with a larger block effect in the taxonomic than in the thematic relation (taxonomic: 627 vs. 576 ms; thematic: 603 vs. 588 ms). The linear mixed effects model analysis confirmed this observation by showing a significant main mixed effect of the block ($\beta = -33.67$, SE $= 7.70$, $t = -4.37$, $p < .001$). A significant interaction between semantic context and block ($\beta = -37.40$, SE $= 12.27$, $t = -3.05$, $p = .002$) was also observed. The main effect of the type of semantic context was not significant (taxonomic vs. thematic: 602 ms vs. 596 ms, $\beta = 6.37$, SE $=$ 26.42, $t = 0.24$, $p = .81$). Separate analysis demonstrated significant interference effects for both types of semantic relations (taxonomic: 51 ms, $\beta = -52.40$, SE $= 11.77$, $t = 4.45$, $p < .001$; thematic: 15 ms, $\beta =$ 15.0, SE $= 7.45$, $t = -2.01$, $p = .044$). Only the taxonomic block effect interacted with cycles (cycle4*context2: $\beta = 44.43$, SE $= 13.00$, $t = 3.42$, $p = .001$), whereas the thematic context did not interact with cycles (ps > 0.06).

5.3.2. Category effect

For the taxonomic task, the average similarity waveforms for taxonomically related, thematically related, and unrelated pairs are displayed in Fig. 7A. A cluster-based permutation test showed that there is a significant difference in similarity between taxonomically related pairs and unrelated pairs ($p = .029$). No significant difference in similarity was found between thematically related pairs and unrelated pairs (*ps* $>$ 0.114). The same analysis was conducted for the thematic task, and the results are displayed in Fig. 7B. The nonparametric cluster-based permutation test showed that there is a significant difference in similarity between taxonomically related pairs and unrelated pairs ($p < .001$). Again, no significant difference in similarity was found between thematically related pairs and unrelated pairs (*ps* > 0.171). In summary, in both tasks, we observed a significant difference in neural activity patterns between taxonomically related pairs and unrelated pairs but no difference between thematically related and unrelated pairs.

5.3.3. Theory-based RSA

The baseline corrected time series for the taxonomic model (Wu-Palmer) and thematic models (LSA and PMI) are plotted in Fig. 8A. No significant cluster was identified for either taxonomic or thematic task (*ps* > 0.34). The results of mean correlation values for Wu-Palmer and each of the thematic models in two tasks within the time window of semantic processing were summarized in Fig. 8B. The ANOVA reveals a non-significant interaction between task and model type and non-significant main effects of task (*ps* > 0.338) for the comparisons between the taxonomic model (Wu-Palmer) or any of the thematic models (LSA/PMI). However, there is a significant main effect of model type ($F(1,30) = 5.87$, $p = .022$), indicating that the neural activity pattern correlates better with the Wu-Palmer similarity matrix than the one constructed based on LSA. For PMI, there is no significant main effect of model type ($F(1,30) = 1.01$, $p = .323$). In summary, the results of theory-based RSA using other thematic measures provide no evidence for a difference between the taxonomic and the thematic tasks.

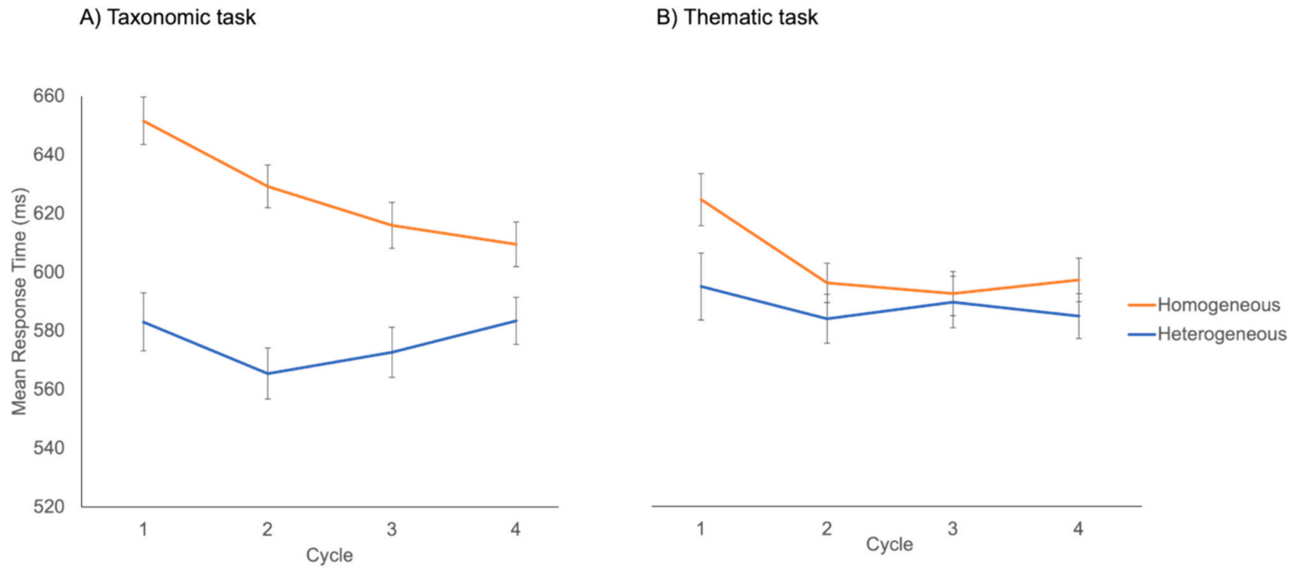

Fig. 6. (A) Mean naming latencies for taxonomically homogeneous vs. heterogeneous blocks; (B) Mean naming latencies for thematically homogeneous vs. heterogeneous blocks. Error bars indicate the standard error of the mean.

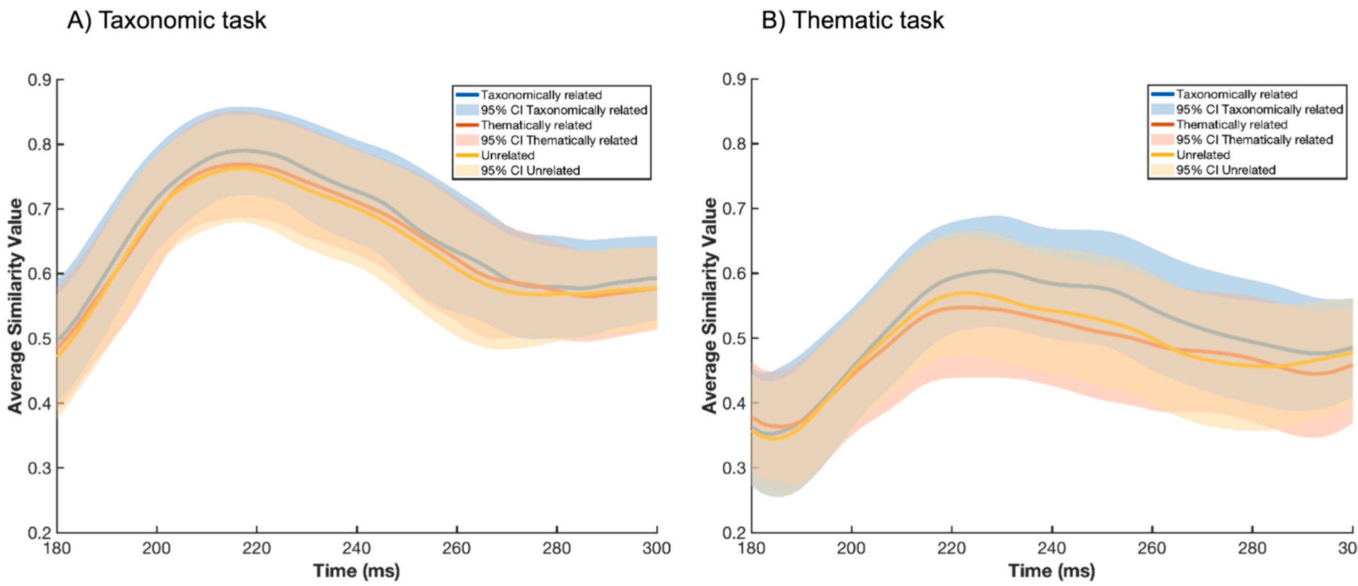

Fig. 7. Time series of averaged similarity values for item pairs within three categories (taxonomically related, thematically related, unrelated) within the time window of 180–300 ms: (A) for the taxonomic task in Study 2; (B) for the thematic task in Study 2.

5.4. Discussion

The analysis of naming latencies reveals that in both taxonomic and thematic versions of the blocked cyclic naming experiment, it took participants more time to name objects when presented in semantically related blocks than when presented in unrelated blocks. However, the interference effect is numerically smaller in the thematic task than in the taxonomic task. These behavioral results are in line with what was found in Abdel Rahman & Melinger (2007, 2011), in which a similar method is used to cue the theme of each block of objects during the learning phase before the thematic blocked cyclic naming task.

The category effect revealed that in both tasks, there was a significant difference between taxonomically related and unrelated pairs in averaged pairwise similarity value, while there was no significant difference in averaged similarity value between thematically related and unrelated pairs, indicating that the neural activity patterns were more similar with taxonomically related items compared to thematically related or unrelated one in both tasks. These results suggested that even in the thematic task that directed participants' attention to the information about the objects' thematic categories, the semantic space was still organized according to the taxonomic knowledge of the objects.

The time window analysis revealed a significant main effect of the model, indicating that the neural activity patterns correlate better with Wu-Palmer similarity compared to LSA within the time course of semantic processing. More importantly, it does not show any evidence of a difference between taxonomic and thematic tasks. None of the two thematic methods showed significant task effects, which is consistent with the results of the category effects as well as the theory-based RSA results of the two existing picture naming datasets. The time series of the averaged similarity values, derived from the theory-based RSA in Study 2, revealed no significant differences between the taxonomic and thematic models in both tasks. The discrepancy between Study 1 Dataset 1

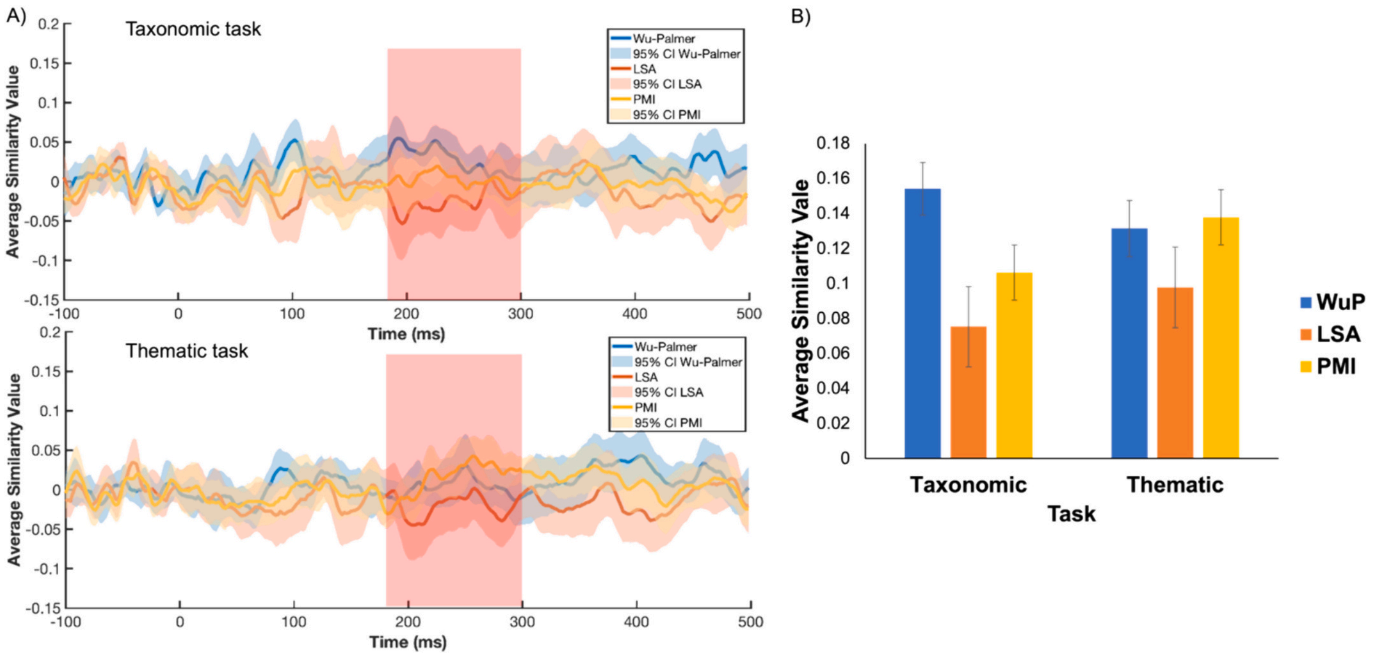

Fig. 8. (A) Baseline corrected time series of average similarity value between EEG-based similarity matrix and theoretical semantic matrices (Wu-Palmer similarity, LSA, and PMI) for the taxonomic/thematic blocked cyclic naming task (Study 2). Time window of 180–300 ms are highlighted. (B) Time window analysis of the taxonomic/thematic blocked cyclic naming study (Study 2). Error bars indicate the standard error of the mean.

and Study 2 might be due to the constraints of the stimuli set used in this study. The stimuli were selected to create both taxonomic and thematic blocks using the same set of items. This design limits our options in choosing objects that meet these requirements, potentially making the contrast between within-category and between category similarity less distinct. For example, compared with Study 1 Data Set 1, Study 2 has a similar level of within-taxonomy Wu-Palmer similarity ($p = .27$) but significantly higher between-taxonomy Wu-Palmer similarity ($p < .001$).

6. General discussion

Semantic knowledge about concepts has been argued to be organized in different ways: based on shared features (taxonomic) or based on co-occurrence in common scenes and scenarios (thematic). Both types of semantic relations have been argued to be co-activated during picture naming (e.g., de Zubicaray et al., 2013; Howard et al., 2006; Rose & Abdel Rahman, 2016; Abdel Rahman and Melinger, 2011; McDonagh et al., 2020). However, which type of semantic system is more accessible and whether the extent to which two semantic systems are accessible depends on task contexts has not been investigated. The present study examines the engagement of different semantic systems in different semantic contexts during picture naming.

To investigate the semantic space underlying picture naming, RSA has been applied to three EEG datasets of picture naming with different semantic contexts: 1) semantic contexts directing attention to taxonomic categories of objects; 2) semantic contexts that do not draw attention to either the taxonomic or thematic structure of objects; 3) semantic contexts drawing attention to either taxonomic or thematic categories of the same set of objects. The RSA results of the three datasets revealed that the neural activity correlates better with taxonomic knowledge than thematic knowledge in all three picture-naming EEG datasets, indicating that taxonomic knowledge played a more dominant role in the semantic space even when taxonomic knowledge is not required by the task contexts or attention is drawn to the thematic relations between objects.

The results of the current research highlights the importance of incorporating different forms of input when investigating taxonomic/thematic systems. Language and perceptual experience of the real world are two major input streams for semantic knowledge. The investigations of corpus-based computational models (e.g., Riordan and Jones, 2011) and sensory-deprived populations (see Bi, 2021) showed that there are two coding systems of semantic knowledge, one sensory-derived and one language-derived. However, the semantic knowledge cued by language might be different from that cued by perceptual information (Lupyan and Lewis, 2019) and such differences likely interact with the taxonomic/thematic distinction. Taxonomic categories are based on shared features intrinsic to the objects themselves that are more likely to be visually available in pictures. Conversely, thematic categories are based on co-occurrence experiences in scenarios and events, it is not possible to be established purely based on the sensorimotor features of isolated objects (Binder, 2016). Therefore, it is possible that in picture naming tasks, the perceptual coding of concepts is more salient, resulting in a more important role of the taxonomic system. Future research is needed to investigate whether other tasks, for example in written word naming, may engage more of the linguistic coding aspects of conceptual processing and increase the engagement of the thematic system. This line of research could offer valuable insights into resolving the discrepancies found in past literature of taxonomic and thematic systems.

The use of EEG-RSA to measure different kinds of semantic cognition is a novel contribution of the current work, allowing us to examine the status of the two co-activated semantic systems during picture naming task. Much of the previous work on semantic cognition has focused on examining whether taxonomic and thematic semantics are two dissociable systems by identifying the brain networks and time courses involved in different kinds of semantic processing, and in the next section, we will discuss our findings in the context of this much larger literature on the neural basis of semantic processing.

With regard to the question of taxonomic and thematic relations, the debate has focused on whether each semantic system has dedicated neural circuitry or not. Mirman et al. (2017) proposed the dual-hub hypothesis of taxonomic and thematic processing to account for the previous findings that two brain regions, ATL and TPC, are involved in semantic cognition (e.g., de Zubicaray et al., 2013; Geng and Schnur, 2016; Henseler et al., 2014; Kalénine and Buxbaum, 2016; Mirman and

Graziano, 2012; Rogers et al., 2004; Schwartz et al., 2011; Teige et al., 2019; Tsagkaridis et al., 2014). They argued that while there is a hub in the ATL specialized for taxonomic knowledge, the TPC was a second semantic hub supporting thematic knowledge processing. However, some studies report a failure to confirm the role of the TPC in processing thematic information (e.g., Kumar, 2018; Lewis et al., 2015), and some studies have implicated the ATL in processing both types of semantic relations (e.g., Jackson et al., 2015; Peelen and Caramazza, 2012; Sass et al., 2009; Xu et al., 2018).

In contrast to these dual-hub accounts, Jackson et al. (2015) propose that a single-hub model could account for both types of semantic relations. In this approach, both taxonomic and thematic relationships are treated as different kinds of features that can be associated with a concept. For example, the thematic relation between the concepts CROISSANT and COFFEE could be captured by allowing the concept CROISSANT to have a "coffee" feature (or an "eaten with coffee" feature). Oppenheim and Nozari (2021) have also argued that thematic relations could be treated as features, like taxonomic relations, when attempting to reconcile the controversy about the behavioral effects of the thematic blocked cyclic naming paradigm in past literature. They conducted a series of simulations demonstrating that when thematic relations are represented as features in the same way as the taxonomic ones, an interference effect was observed. Conversely, when thematic information is only weakly associated with the conceptual cores, it acts as a retrieval cue and provides contextual support, resulting in a facilitation effect. Study 2 of the present research demonstrated an interference effect in the thematic blocked cyclic naming task, though it was weaker than that observed in the taxonomic version of the task. Two possibilities could explain this outcome: one is that the thematic relations were considered a kind of feature of the objects, and the other is that both forms of representations are operational, with the weaker inference being a result of their combination.

While treating thematic relationships as a kind of semantic features just like taxonomic relations has an appealing simplicity, how exactly the thematic features are represented is not clear. If the CROISSANT has a "coffee" feature, then the COFFEE concept should also be attached with a "croissant" feature. Then the two thematic features would have nothing in common despite the two concepts forming a common theme. The RSA results of Study 2 show that even if the thematic information was regarded as a feature associated with the concept, the taxonomic feature is more salient than the thematic features, and the concepts are organized in semantic space according to the taxonomic knowledge of the concepts. This finding cannot be explained by the difference in general relatedness between the two types of object pairs (taxonomically/thematically related). As indicated by the subjective ratings of general relatedness of the taxonomically related pairs and thematically related pairs in Study 2, human subjects regarded the thematically related pairs as more associated with each other compared to the taxonomically related pairs. This finding supports what Landrigan and Mirman (2018) argued in their study: the taxonomic and thematic relations are distinctly processed or represented. Even if the thematic relationships are based on features, the thematic features are fundamentally different from those that support taxonomic relationships. Alternatively, the two types of features are integrated differently, requiring distinct mechanisms to process them.

The present research also speaks to the potential limitation of conceptual flexibility predicted by leading theories of semantic cognition. For example, Yee and Thompson-Schill (2016) argued that context is a fundamental property of the structure of the semantic system and cannot be meaningfully separated from the concept. The dual-hub theory (Mirman et al., 2017) and Controlled Semantic Cognition (CSC) framework (Jefferies et al., 2020; Lambon Ralph et al., 2017) also predict flexibility in terms of the extent to which the taxonomic and thematic systems are activated under different task demands. However, we fail to find evidence of extensive flexibility of the two systems when the task goal – naming a picture – remains the same while the task context varies. However, other experimental conditions, using somewhat analogous approaches to our own, have found that when the task goal changes, more semantic flexibility is observed. Specifically, when individuals are asked to explicitly attend to certain properties of the stimuli, changes in the neural representational structure of a common set of stimuli have been reported (e.g., Harel et al., 2014; Hebart et al., 2018; Nastase et al., 2017). We contrast our results with those previous results, pointing out that we are examining a different, more subtle, type of task context effect on conceptual representations. Although the semantic contexts in which the objects appear did affect the naming latency, the RSA results consistently showed that these objects are stably organized in semantic space according to their taxonomic relations, suggesting that conceptual representations are at least not as flexible as argued by the most flexible account of semantic cognition (e.g., Connell and Lynott, 2014; Yee and Thompson-Schill, 2016). More research is required to investigate the boundaries of conceptual flexibility in different circumstances to get a better picture of how the human cognitive system processes conceptual knowledge.

Limitations and Future Directions.

The current research focuses solely on examining the status of taxonomic and thematic systems during picture naming tasks. The hypothesis that the form of input for semantic processing interacts with taxonomic/thematic distinctions warrants further investigation, potentially using other tasks. For instance, word reading tasks might engage more of the linguistic coding aspects of conceptual processing, rather than the perceptual coding aspects. This could lead to a higher level of activation of the thematic system, compared to picture naming tasks. Future work will have to investigate this possibility to gain a more comprehensive understanding of the two semantic systems.

Moreover, the EEG studies in the current research only manipulated the semantic context in which the objects appear; The tasks participants performed in the three datasets are all picture naming. Compared to the manipulation of semantic context, altering the behaviors participants performed likely has a more profound impact on the neural representations of taxonomic and thematic systems. Therefore, to get a full picture of semantic organization underlying different tasks and whether it is compatible with theories of semantic cognition, a further investigation to pit against different aspects of the task demands with each other is needed. Since prominent theories of semantic knowledge such as dual-hub theory and the CSC framework made predictions on brain regions involved in taxonomic and thematic processing, respectively, fMRI data could be obtained to provide converging evidence for the task effects on taxonomic and thematic processing in the brain regions engaged in the semantic network.

Another limitation of the current research is that the null effect of task contexts observed in the theory-based RSA results of Study 2 constrained our ability to draw definitive conclusions about semantic flexibility. It is possible that task contexts did influence the engagement of taxonomic and thematic systems, but the changes were not significant enough to detect in current design. Although the present data do not allow for strong claims regarding semantic flexibility, our intention is to contribute to the field by raising the hypotheses of conceptual flexibility made by two leading theories, for no prior research has directly compared these two theories in terms of their predictions regarding conceptual flexibility. Future investigations are necessary to test these hypotheses.

The current research demonstrated that RSA is a promising method for assessing how well the representational similarity structure predicted by a theoretical semantic model resembles the neural similarity structure observed from neuroimaging data. This method can be applied to understand the engagement of different types of semantics by looking at the RSA results across different task contexts. However, the inadequate understanding of the nature of thematic relations limited the capability of building computational models to characterize thematic relations. Even the most used thematic measures, LSA and PMI, only capture some aspects of the thematic relations. The assessment of LSA and PMI (Zhai, 2022) indicated that while LSA and PMI moderately correlate with the subjective judgments of thematic relatedness, there is unexplained variance, and some of them might be a consequence of the reliance on the distributional measures on the statistical regularities extracted from texts. A recent RSA study (Fernandino et al., 2022) has compared different types of computational models and demonstrated the potential of experiential models that encode information about the experiences that led to the formation of concepts. In future studies on semantic cognition, different types of computational models can serve as useful tools in combination with a decoding approach to investigate the content and format of the different types of semantic representations.

7. Conclusion

In summary, the present study tested the hypothesis about whether and how taxonomic and thematic relations are engaged during picture naming, and whether the activation of these relations are influenced by semantic contexts. We approached this question analytically using RSA, a multivariate approach that allows us to draw connections between similarity structures derived from neuroimaging data and computational models of semantics under different task contexts. The current study investigated datasets of a series of picture naming tasks with different semantic contexts and found that at least in picture naming tasks, concepts are organized according to taxonomic knowledge in semantic space.

CRediT authorship contribution statement

Mingjun Zhai: Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Chen Feng:** Writing – review & editing, Visualization, Software, Methodology, Formal analysis, Data curation. **Qingqing Qu:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition, Conceptualization. **Simon Fischer-Baum:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization.

Declaration of competing interest

None.

Data availability

The data will be publicly shared upon publication

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