



# Delta-band Activity Underlies Referential Meaning Representation during Pronoun Resolution

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## Abstract

Human language offers a variety of ways to create meaning, one of which is referring to entities, objects, or events in the world. One such meaning maker is understanding to whom or to what a pronoun in a discourse refers to. To understand a pronoun, the brain must access matching entities or concepts that have been encoded in memory from previous linguistic context. Models of language processing propose that internally stored linguistic concepts, accessed via exogenous cues such as phonological input of a word, are represented as (a)synchronous activities across a population of neurons active at specific frequency bands. Converging evidence suggests that delta band activity (1–3 Hz) is involved in temporal and representational integration during sentence processing. Moreover, recent advances in the neurobiology of memory suggest that

recollection engages neural dynamics similar to those which occurred during memory encoding. Integrating from these two research lines, we here tested the hypothesis that neural dynamic patterns, especially in delta frequency range, underlying referential meaning representation, would be reinstated during pronoun resolution. By leveraging neural decoding techniques (i.e., representational similarity analysis) on a magnetoencephalogram data set acquired during a naturalistic story-listening task, we provide evidence that delta-band activity underlies referential meaning representation. Our findings suggest that, during spoken language comprehension, endogenous linguistic representations such as referential concepts may be proactively retrieved and represented via activation of their underlying dynamic neural patterns. ■

## INTRODUCTION

Consider the meaning of the pronouns *she* and *herself* in the following passage:

*“The fool doth think [she] is wise, but the wise [woman] knows [herself] to be a fool.”*

Adapted from Shakespeare’s *Twelfth Night*.

To understand the above passage, we have to combine the previously presented story agent (i.e., “the fool”) with the pronoun *she* to understand that it is the fool who considers herself wise; then, we must understand that *herself* refers to *the wise woman* but not *the fool*. Thus, to comprehend the sentence, or any event involving a pronoun, some form of memory of the matching antecedent must come into play when the pronoun is processed. Pronouns are ubiquitous in human language, and their use and interpretation is a cornerstone of human cognition (e.g., Garrod & Sanford, 1994) and development (e.g., Hendriks & Spender, 2006). However, how this quintessential linguistic device is realized in neural terms, such that it enables us refer to agents, events, and concepts that span

time and space, is not well understood. Furthermore, pronoun processing sits at the intersection between language and memory, offering a fruitful way to study the interplay between these two types of information in the brain.

A burgeoning cue-based account of language in the brain (e.g., Martin, 2016, 2020) has proposed that comprehension is a perceptual inference process whereby the brain takes exogenous cues (e.g., sensory features) as its input and combines them with endogenously generated linguistic cues (e.g., lexical entries, procedural syntactic rules) from memory to achieve comprehension. Pronoun resolution thus also fits into this account as it requires access to previously encoded entities or concepts to integrate them in turn with roles the pronoun plays, so that coherent construction of events in a text or conversation can be achieved. Indeed, supporting evidence has emerged from a plethora of studies showing that properties of both external and internal cues (e.g., featural match/mismatch, referent prominence), as well as how they are combined, can influence how the brain resolves a pronoun (Lissón et al., 2021; Coopmans & Nieuwland, 2020; Nieuwland, Coopmans, & Sommers, 2019; Parker, 2019; Karimi, Swaab, & Ferreira, 2018; Brodbeck & Pykkänen, 2017; Brodbeck, Gwilliams, & Pykkänen, 2016; Chow, Lewis, & Phillips, 2014; Nieuwland, 2014; Nieuwland & Van Berkum, 2008; Foraker & McElree, 2007; Ledoux, Gordon, Camblin, & Swaab, 2007). Yet, the neural mechanism by which a referent concept is retrieved and

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represented in memory when the brain resolves a pronoun has barely been discussed. Major neurobiological findings regarding pronoun resolution come from studies using the ERP technique, which have identified an increased, sustained anterior negative component (i.e., Nref) induced in pronouns that are incongruous with their antecedent (e.g., Nieuwland, 2014) or ambiguous in their reference (e.g., Coopmans & Nieuwland, 2020; Karimi et al., 2018; Nieuwland & Van Berkum, 2008). However, although these results provide evidence in favor of the cue-based account by showing that retrieving internally stored entity representations can be interfered by processing referentially incoherent or ambiguous input, they do not give a clear picture how the brain actually accesses referent concepts. Additionally, the modulation of neural activities by mismatch or ambiguity of pronouns are subject to other possible interpretations based on domain-general cognitive functions, for instance, enhanced attentional process because of error or ambiguity detection. In other words, a converging mechanistic account of how the retrieval of a referent concept from memory is accomplished in the brain remains a missing puzzle from existing studies on referential resolution.

Recent advances in the domain of neuroscience of memory have provided insight into memory retrieval through neural decoding techniques. Numerous findings have indicated that neural patterns during memory encoding are reinstated during memory retrieval (e.g., Ten Oever, Sack, Oehm, & Axmacher, 2021; Pacheco Estefan et al., 2019; Staresina et al., 2019; Jang, Wittig, Inati, & Zaghoul, 2017; Xiao et al., 2017; Yaffe, Shaikhouni, Arai, Inati, & Zaghoul, 2017; Yaffe et al., 2014; Manning, Sperling, Sharan, Rosenberg, & Kahana, 2012; Johnson & Rugg, 2007). In particular, oscillatory neural dynamics, often referred to as putative neural oscillations and postulated to arise from an ensemble of neurons firing synchronously, have been found reinstated during recollection (e.g., Ten Oever et al., 2021; Staresina et al., 2019; Yaffe et al., 2017; Yaffe et al., 2014; Nyhus & Curran, 2010). Among these studies, representational similarity analysis (RSA), that is, a measurement of the similarity between neural states during memory encoding and retrieval acquired through multivariate pattern analysis, has been applied to investigate the reinstatement of previous activity patterns as a brain mechanism for retrieval. Relevant to language processing, such effects have also been observed during word retrieval (Ten Oever et al., 2021; Yaffe et al., 2017; Yaffe et al., 2014). It has been shown that theta- (3.5–8 Hz) and gamma-band (50–100 Hz) activity underlying word learning was reinstated during successful word recall in a verbal association task (e.g., Yaffe et al., 2017, 2014). In addition, in this same line of research, converging evidence has shown that the temporal lobes, including both lateral temporal (e.g., the fusiform gyrus, middle temporal gyrus; Jang et al., 2017; Johnson & Rugg, 2007) and medial temporal regions (e.g., hippocampus; Manning et al., 2012), are engaged in reinstatement of memory traces (Pacheco Estefan et al., 2019;

Staresina et al., 2019) and, importantly, lexical retrieval (Ten Oever et al., 2021). Altogether, these results provide evidence that the reinstatement of neural-oscillatory responses underpinning memory traces in both lower- and higher-frequency bands (e.g., theta and gamma), particularly across temporal regions, is involved as memory representations during retrieval.

Consistent with memory findings indicating that oscillatory dynamics play a role in memory retrieval, the cue-based retrieval account of language processing purports that linguistic cues, either external or internal, can be represented by neural oscillations (e.g., Martin, 2016, 2020) and serve to elicit or “serve up” existing information in the brain—implicitly, this claim indicates that that process must rely on some forms of memory. Indeed, a body of research bridging neural oscillations and language processing has suggested that the human brain’s ability to form representations from abstract linguistic symbols is enabled by multiplexing of its rhythmic activities on various timescales to impose internal knowledge upon external, incoming input (Gwilliams, 2020; Martin, 2020; Martin & Doumas, 2017, 2019, 2020; Meyer, Sun, & Martin, 2020; Meyer, 2018; Rimmele, Gross, Molholm, & Keitel, 2018; Kösem & van Wassenhove, 2016). It has been shown that neural oscillations are involved in not only the processing of sensory streams (e.g., Kösem et al., 2018; Luo & Poeppel, 2007) but also in the processing of higher-order linguistic representations (e.g., Bai, Meyer, & Martin, 2022; Coopmans, de Hoop, Hagoort, & Martin, 2022; Henke & Meyer, 2021; Kaufeld, Bosker, Alday, Meyer, & Martin, 2020; Brennan & Martin, 2020; Meyer, Henry, Gaston, Schmuck, & Friederici, 2017; Ding, Melloni, Zhang, Tian, & Poeppel, 2016). Concretely, delta-band activity (1–3 Hz) has been found to be relevant for the tracking of meaningful linguistic elements such as words and phrases (e.g., Ten Oever, Carta, Kaufeld, & Martin, 2022; Henke & Meyer, 2021; Kaufeld et al., 2020; Meyer et al., 2017; Ding et al., 2016). However, it remains an open question how activity in the delta band is involved in this process, or rather, it remains unclear what precisely modulations of delta represent in terms of neural information processing. Besides the role of tracking higher-level linguistic components from sensory input as suggested by the aforementioned studies (also see Lakatos, Gross, & Thut, 2019; Rimmele et al., 2018), another postulated role of delta has been proposed, that is, as a functional pattern that reflects the generation of abstract linguistic representations (e.g., Ten Oever & Martin, 2021; Martin, 2020; Meyer et al., 2020). This creation or generation of structure and information likely entails recognition, reactivation, or retrieval of information from memory. In the current study, by investigating the neural-oscillatory substrates of pronoun resolution, we aim to focus on this postulated, top-down function of delta in imposing previously encoded memory representations on incoming speech. Pronoun processing necessarily requires the brain to recover higher-order linguistic elements that are previously stored in memory, instead of

simply tracking them directly from the sensory input of a pronoun *per se*. In this case, if modulations of delta-band activity, importantly reinstatement of delta activity underlying referent representation, were indeed found when the brain resolves a pronoun and constructs the corresponding event, then it would support the proposal that delta activity is involved in the retrieval of stored higher-order linguistic representations or in the integration of that information with its current role in the sentence or discourse. Given that pronouns can vary in the time duration they take up in speech processing, both within and across languages, finding evidence for effects of pronoun retrieval and integration in the delta band would support a functional account of frequency bands that is not necessarily tied to the absolute, external timing of stimulus presentation, but rather more endogenous and abstract, during language comprehension. Therefore, investigating the rhythmic neural responses underlying pronoun resolution serves as a promising opportunity to better understand the mechanistic roles oscillatory neural dynamics play in language processing.

Therefore, in light of oscillatory neural activation reinstatement as an emerging account of memory retrieval, the current study seeks to investigate whether referent concept representation during pronoun resolution also engages the reinstatement of oscillatory activities underlying antecedent processing in the brain—although (separately), existing findings have suggested the involvement of neural pattern reinstatement and oscillatory responses in pronoun resolution (Zhang, Li, Yang, & Hale, 2022; Coopmans & Nieuwland, 2020; Nieuwland & Martin, 2017). Several EEG findings (Coopmans & Nieuwland, 2020; Nieuwland & Martin, 2017; Meyer, Grigutsch, Schmuck, Gaston, & Friederici, 2015) identify enhanced power of rhythmic brain responses such as theta and gamma when the brain processes pronouns coherent with their corresponding antecedent. Meanwhile, a decoding study by Zhang and colleagues (2022) found activation in the left middle temporal gyrus that underpinned the presentation of story characters during the processing of zero pronouns (i.e., an obligatory noun phrase that serves a role in an event but is not overtly pronounced in the utterance) in Mandarin Chinese. By leveraging RSA, the study managed to zoom in and compare neural responses between individual items (i.e., each referent and zero pronoun), which have largely been smeared out by grand-averaged patterns of two coarse lexical categories as in traditional condition-based statistical analyses. This way, hypotheses about item-specific neural fluctuations (in this case reinstatement) were tested. Therefore, by adopting RSA as the neural decoding technique, the current study aimed to provide first direct evidence that oscillatory neural responses underlie referent representation via reinstatement during pronoun processing.

The main question we ask in this study is whether rhythmic neural patterns underlying processing of the antecedent of a pronoun are reinstated when that pronoun is resolved during spoken language comprehension. To answer the question, we conducted RSA on responses to

pronouns and their noun antecedents extracted from a magnetoencephalogram (MEG) data set, which was recorded while participants listened to continuous audiobook stories in Dutch. We predict that neural responses associated with higher-order linguistic elements, that is, modulations of the delta frequency range—in this case, those responses associated with the antecedent noun—are more likely to recur systematically during pronoun resolution, and thus reinstating the rhythmic neural patterns of the antecedent during pronoun resolution. Besides, given that theta- and gamma-band activity have also been found associated with word retrieval (e.g., Ten Oever et al., 2021; Yaffe et al., 2014, 2017) and also referential resolution (e.g., Coopmans & Nieuwland, 2020; Nieuwland & Martin, 2017; Meyer et al., 2015), we predict that reinstatement of theta and gamma responses that underlie referential noun processing will also be observed when the brain processes a pronoun.

However, as we are measuring pronoun resolution during naturalistic story listening, we are necessarily investigating a situation where pronouns occur in the context of supportive discourse. A crucial difference for naturalistic story listening, as compared with highly controlled experimental manipulations, is that pronouns only occur when they are licensed—when the information they refer to is given, predictable, and expected. Thus, it is possible that the brain will engage predictive processing to support the retrieval of pronouns in natural discourse contexts (Wolf, Gibson, & Desmet, 2004). If this is the case, then activity in the delta band may reflect the predictive nature of pronoun resolution (Foraker & McElree, 2007).

## METHODS

### Participants

Twenty-nine participants (21 women; mean age: 37.14 years old) with normal hearing and no history of psychiatric, neurological, or other medical illness that might compromise cognitive functions took part in the experiment. They identified themselves as native Dutch speakers and self-reported having little or no prior knowledge of French. All participants gave informed consent before the experiment and received monetary compensation for their participation. This study was approved by the Ethical Commission for Human Research Arnhem/Nijmegen (Project Number CMO2014/288). Data sets of three participants were removed from further analyses, as two participants did not complete the experiment, and one other wore dental wires during the recording session. Twenty-six participants<sup>1</sup> were included in all analyses.

### Stimuli and Paradigm

In the experiment, participants were instructed to listen to audiobook stories while their MEG responses were being measured. The audiobook stimuli consist of three Dutch stories and three French stories presented in a pseudorandomized

order. The Dutch stories include Anderson's *Het Leelijke Jonge Eendje* and Grimm's *De Ransel, het Hoedje en het Hoorntje* and *De gouden vogel*, and the French stories Anderson's *L'Ange*, Grimm's *L'eau de La Vie*, and E.A. Poe's *Le Canard au ballon*. In this study, we focus on the Dutch stories. The French stories were collected as part of a long-term commitment to collect a bigger MEG set of naturalistic audiobook listening including the option for cross-language comparison, which was not part of this study.

All stories were split into blocks lasting approximately 5 min each; this way, participants were each presented with 13 blocks (nine blocks for Dutch stories and four for French stories). Before each block, each participant's resting state brain activity was recorded for 10 sec. Between each two blocks, participants were indicated to answer five multiple-choice comprehension questions based on the story content they have just heard to ensure they paid attention to the stimuli. Including setup and breaks, the entire MEG session took an average of 90 min.

Before the experiment, each participant completed a 5-min, MEG auditory localizer task whereby they listened to tones while the brain responses were recorded. They also underwent MRI structural scanning before or after the MEG session.

## Data Recording

MEG data were recorded using a 275-channel, whole-brain axial gradiometer system (CTF VSM MedTech) at a sampling rate of 1200 Hz. Bipolar VEOG and HEOG and electrocardiogram were recorded using Ag/AgCl-electrodes. Six channels were permanently faulty and two others successively disabled during the recordings, leaving 269 recorded MEG channels for 23 participants and 267 for three participants. Head localization was monitored continuously during the experiment using fiducial coils that were placed at the cardinal points of the head (nasion and bilateral ear canals). The fiducial coils also served as anatomical landmarks for co-registration with MRI scans during source reconstruction. Stimulus presentation was controlled by the MATLAB (The MathWorks) toolbox *Psychtoolbox*. Immediately after the MEG session, each participant's headshape and position of three fiducial points were recorded using a Polhemus 3-D tracking device.

The T1-weighted MRI scan of each participant was acquired on one of three 3 T MRI scanners (Siemens) available at the Donders Institute. Earplugs with a drop of vitamin E were placed at the participant's ear canals during MRI acquisition, to facilitate co-registration between MEG and MRI data.

## Analyses

### Target Word Selection

For pronoun word stimuli, we selected all Dutch personal (subject and object), possessive, and reflexive pronouns

(except second-person ones). For referent words, we picked out the main noun of noun phrases referred to by the chosen pronoun words. In the end, 791 pronouns and 407 referent nouns in the Dutch audiobook stories were selected as target words. Out of the 791 pronouns, there were 57.3% (452) subject pronouns (e.g., *ik* [I], *bij* [be], *zij* [she/they], *wij* [we]), 21.7% (171) object pronouns (e.g., *mij* [me], *hem* [him], *haar* [her], *ons* [us]), 18.3% (144) possessive (e.g., *mijn* [mine], *zijn* [his], *hun* [their], *ons/onze* [our]), and 2.7% (21) reflexive (e.g., *zelf/zich* [self]) pronouns.

### Part-of-speech Variability Metrics

To quantify the linguistic context around or pronouns and nouns we analyzed the part-of-speech (POS) variability of preceding and following seven words of target words for referent nouns and pronouns separately. We chose to analyze  $\pm 7$  word positions because the average word duration in the Dutch audiobook stories were 0.247 sec, and we therefore believe that including seven words in the metrics would cover the time window of our delta power similarity effects (i.e.,  $-0.6$  to  $1.5$  sec) sufficiently. POS-tag information was generated by Universal Dependencies 2.0 (Straka & Straková, 2017; <https://universaldependencies.org/>). For POS variability results, see Appendix 5.

### Preprocessing and Time-Frequency Analyses

MEG data were preprocessed using Fieldtrip toolbox (Oostenveld, Fries, Maris, & Schoffelen, 2011) running under MATLAB 2021a. Data were first epoched as  $-2$  to  $3.5$  sec around word onset and downsampled to 300 Hz with an anti-aliasing, low-pass filter applied before resampling. Artifact detection and rejection was conducted to remove trials that contained muscular and jump noise; during this process, the artifacts were first identified automatically and then subjected to manual rejection. Independent component analysis was then performed to remove components including ocular movements, slow drifts, heartbeat, and other salient noise. All the data sets were then subjected to a time-frequency analysis, yielding both power and phase. Activity at low frequencies (1–30 Hz) underwent a wavelet analysis (1-Hz step size), with variable widths from 3 to 10 cycles (linearly increasing across frequencies) and a time range of  $-0.5$  to  $2$  sec (0.05-sec step size). For higher frequencies (35–150 Hz), a multitaper analysis (dpss taper; 10 cycles data at a 0.5-cycle smoothing) was conducted with a step size of 5 Hz. All power values from the analyses were log-transformed by single trial per frequency. We chose to not conduct baseline correction as 502 of the 1198 trials have at least one target word stimulus from other trials present within 1.5 sec preword onset. Given the structure of the naturalistic stimulus, baseline correction raises the possibility of introducing noise from the prestimulus period into



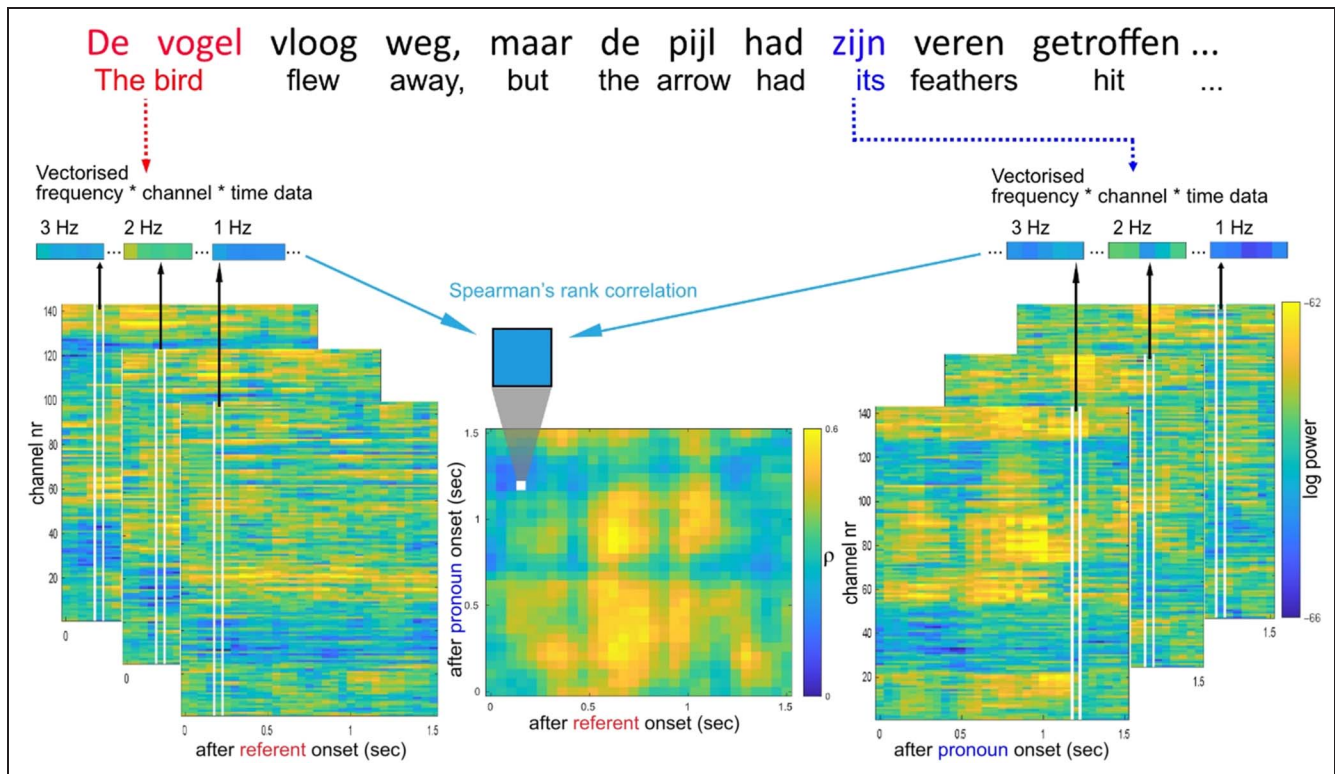
poststimulus, thereby biasing the observed difference between the two conditions.

### Sliding-window RSAs

In light of previous findings suggesting that the temporal cortex is involved in reinstatement and maintenance of lexical representations (e.g., Zhang et al., 2022; Ten Oever et al., 2021; Jang et al., 2017; Yaffe et al., 2017), in the current study, we used bilateral temporal channels. Spearman correlations were computed for each pair of referent and pronoun trials across all sensor channels in the bilateral temporal regions. To investigate the specific time periods in which the effect takes place, we adopted a sliding-window approach on time axes of both referent and pronoun trials (see Figure 1); that is, for a pair of a pronoun and a referent trial, a 50-msec wide sliding window was moved on the two trials, respectively, in a time range between 0 to 1.5 sec time-locked to stimulus word onset. The choice of the time window of 0–1.5 sec for RSA was driven by prior ERP literature (e.g., Coopmans & Nieuwland, 2020; Nieuwland et al., 2019; Nieuwland & Van Berkum, 2008), which indicated 0–1.5 sec as being relevant to pronoun resolution. Then, correlations were computed between vectorized frequencies  $\times$  channels  $\times$  time datapoints of the two trials in a pair for each of the 50-msec time

bins. This resulted in 900 (30  $\times$  30) pronoun  $\times$  referent time  $\times$  time units in a temporal generalization map. By contrasting between the values produced by correlating matching and nonmatching pronoun–referent pairs, we tested the similarities between neural activities of referent and pronoun processing, that is, the reinstatement of referent representations during pronoun resolution. A simulation of the word pairing process to generate datapoints in the matching and nonmatching antecedent–pronoun conditions is shown in Appendix 2. The correlations and cluster-based statistics were conducted on each band separately, namely, delta (1–3 Hz), theta (4–7 Hz), alpha (8–12 Hz), beta (13–20 Hz), and low-gamma (35–80 Hz). Note that given prior findings on the oscillatory correlates of pronoun resolution, we took particular interest in the delta, theta, and low-gamma bands.<sup>2</sup> Spearman correlations were conducted on power values, and circular–circular correlations on phase values using the *CircStat* toolbox (Berens, 2009).

As neural activity adjacent in time tends naturally to be similar and as such could cause inflation of similar results, we took two primary measures to prevent such inflation. First, we selectively included nonmatching referent–pronoun word pairs for the computation of similarities so that the median word count distances in the two conditions remained identical. This means that the similarity



**Figure 1.** Computing RSA for each pair of pronoun and referent trials. Here, we take delta-band (1–3 Hz) as an example. The plots on the left and right show, respectively, time–frequency power patterns of the delta band of a referent and a pronoun trial. To compute the similarity between the two trials at a certain time  $\times$  time unit, vectors of all frequencies (per band)  $\times$  channels  $\times$  time points were built. For power, the Spearman's rank correlation coefficient between the pronoun and referent trial vectors determines the value of a single datapoint (i.e., time  $\times$  time point) in a temporal generalization map. For phase, the value is determined by the circular–circular correlation coefficient, computed using *CircStat* toolbox (Berens, 2009).

caused by temporal adjacency does not confound the results as the mean distance between target words is the same in both conditions, and thus, any effect of time proximity is factored out. This criterion was implemented by systematically removing nonmatching referent–pronoun pairs to match the median temporal distance of the matching pronoun pairs (which were much fewer in number). Second, we also excluded any pair of words whose onset difference was within 1.5 sec. This was to ensure to never correlate identical data with each other, given that the RSA involves a sliding window moving time bins up to 1.5 sec apart.

To further exclude the possibility that the observed effects were confounded by other random stimulus words that overlapped with a trial, we removed any referent–pronoun trial pair wherein other stimulus words were included that had the same reference in general. This ensured that the similarity effects we observed were only because of the processing of the word pairs that defined the trials. Note that to do this, we not only removed pairs of matching referents and pronouns whose onset difference was within 1.5 sec, but nonmatching referent–pronoun pairs that met the criteria as well.

We performed four different control RSAs. First, to better understand the temporal dynamics of reference resolution that were identified in pronoun–referent RSAs, we also conducted an RSA between referent words and between pronoun words, respectively (namely, word control RSAs). Concretely, we compared similarity values between pairs of words identical in form and those composed of differently formed words, irrespective of their reference. This should reveal the neural patterns evoked by perceptual and semantic features of single words. Same as on pronoun–referent stimulus word pairs, we conducted here the median word count control between identical and non-identical words pairs, as well as the exclusion of trial pairs where one trial contained overlapping word stimuli identical to any word stimulus in the other.

As a second control analysis, we investigated the influence of prepronoun activation in the power analysis. To do this, a sliding-window RSA was performed between  $-1$  and  $0.2$  sec time-locked to pronoun onset and between  $0$  and  $1.5$  sec postreferent onset keeping all other RSA parameters identical.

A third control analysis investigated the influence of different baseline corrections. Instead of using no baseline corrected, we used a baseline of either  $-0.3$  to  $-0.1$  or  $-1$  to  $-0.8$  sec time-locked to word onset. The baseline correction was conducted on each frequency separately after time–frequency analysis and before the data entered the RSA. In this analysis, we conducted RSA on a subset of trials where no other target stimulus word (pronoun or referent noun) precedes the trial defining word within a temporal distance of  $1.5$  sec to ensure that this did not influence the baseline. The subset contained 696 trials (466 pronouns and 230 referent nouns). Note though that for delta power estimation in the case here, a wavelet

analysis with variable widths from 2 to 10 cycles (linearly increasing across frequencies) was conducted to accommodate a longer estimation time range before word onset (i.e.,  $-1$  to  $0$  sec).

In our final control analysis, we investigated whether there were any acoustic similarities between matching and nonmatching pronoun–referent pairs that would explain our effect. An RSA was performed between spectrograms of pronouns and referent nouns. For each target stimulus word, a spectrogram (20–22050 Hz,  $-0.5$  to  $1.5$  sec) was computed per 50-msec sliding window (using *spectrogram()* under MATLAB 2023b) based on the wav-file of each part of audiobook stories. Subsequently, the power values of all frequencies in the spectrogram of each sliding window were put into a sliding-window RSA. We conducted the acoustic RSA between pronouns and referent nouns and also between only referent nouns. We kept here the selection of word pair in which we conducted original RSAs. Note that we did/could not do the cluster statistics here because there was no intersubject variance. Therefore, we can only look at descriptive similarities between acoustic and neural RSA.

### Statistical Testing

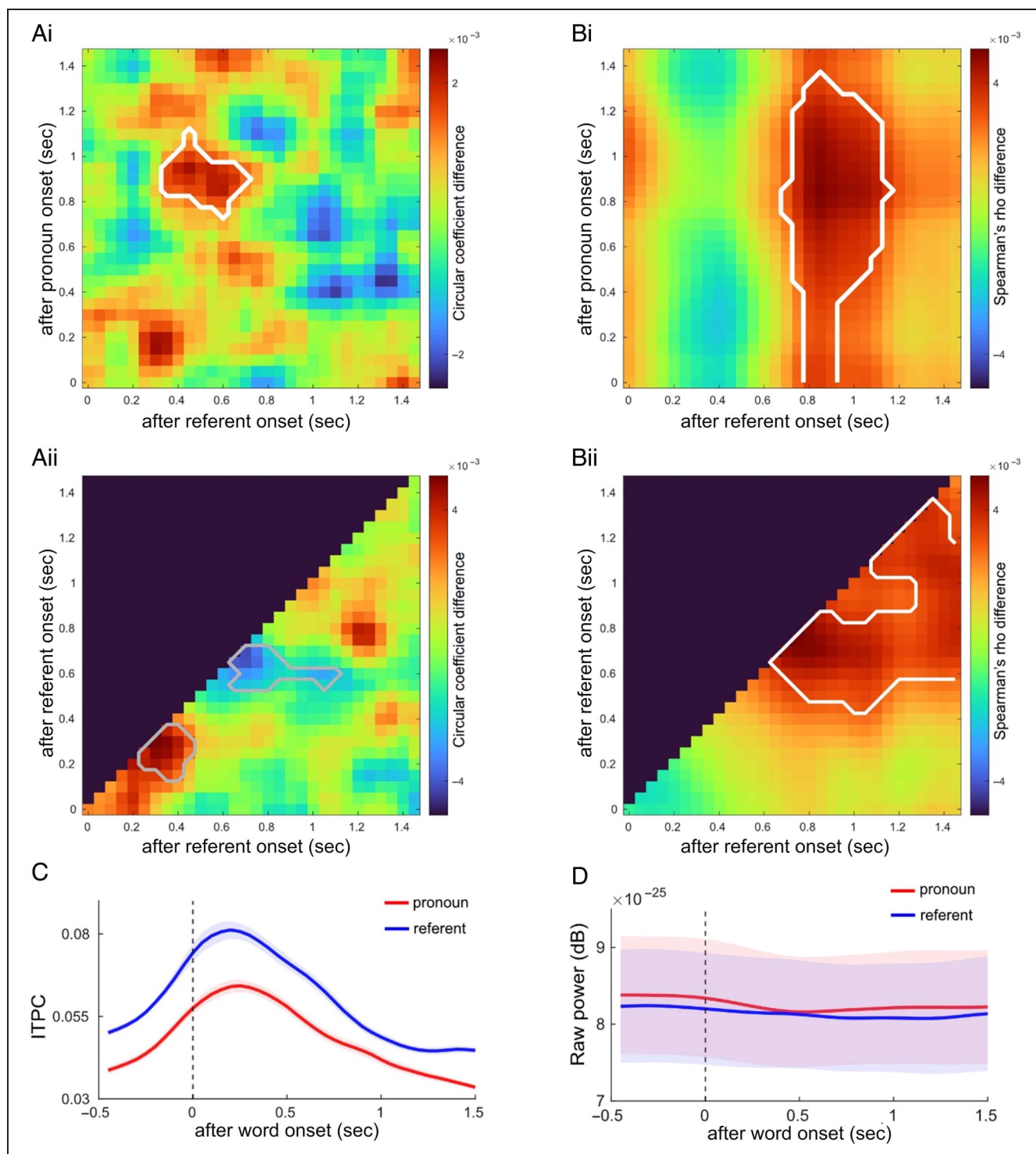
Averaged matching and nonmatching pronoun–referent (or word–word) correlation values were compared statistically using dependent-samples *t* tests across participants in each pronoun  $\times$  referent time  $\times$  time unit. Cluster-based permutation tests were performed to correct for multiple comparisons (Maris & Oostenveld, 2007). Clusters were defined as a group of neighboring time  $\times$  time units with a *p* value lower than .05 each in the dependent-samples *t* tests. The sum of *t* values of time  $\times$  time units in a cluster was defined as the dependent variable on the cluster-level statistics. A distribution was then created by randomly permuting condition labels for 10,000 times across participants and recomputing the test statistics produced by each permutation. The surrogate clusters with the maximum summed *t* values entered the null distribution. Significance level (*p* values) was then defined as the proportion of surrogate clusters in the distribution whose summed *t* values were higher than those of the cluster observed from the actual data. We rejected null hypotheses when *p* values were smaller than .05.

## RESULTS

### Delta Band (1–3 Hz)

#### Phase

In the pronoun–referent phase RSAs, a significant stronger Spearman correlation was found for the matching versus nonmatching pronoun–referent pairs (Figure 2Ai; *p* = .0443; matching: cluster mean = 0.0117; nonmatching: cluster mean = 0.0100). These results suggested that the phase of delta-band oscillations during referent



**Figure 2.** Similarity of referent-related delta-band (1–3 Hz) activities during pronoun resolution. (A) Similarity of neural representations of referent words is found in the delta-band phase during pronoun resolution. (i) Temporal generalization map averaged across participants for the difference between matching and nonmatching pronoun–referent word pair conditions. (ii) Averaged temporal generalization map for the difference between formally identical and non-identical word pair conditions. Regions highlighted with white outlines indicate significant difference at the  $p = .05$  level, whereas those highlighted in gray indicate trend-significant difference. (B) Similarity of neural representations of referent words is found in delta-band power during pronoun resolution. (i) Temporal generalization map averaged across participants for the difference between matching and nonmatching pronoun–referent word pair conditions. (ii) Averaged temporal generalization map for the difference between formally identical and non-identical word pair conditions. Regions highlighted with white outlines indicate significant difference at the  $p = .05$  level, whereas those highlighted in gray indicate trend-significant difference. (C) Uncorrected, mean ITPC averaged per temporal channel per delta frequency. The ITPCs of pronoun and referent trials were plotted as separate lines. Note that the higher ITPC for referent words here could be because of the fact that the number of referent word trials are smaller than that of pronoun word trials. (D) Mean delta power across the delta band and across all temporal channels. The mean power of pronoun and referent trials was plotted as separate lines. Shaded error bars indicate the standard error of the mean.



representations was activated during pronoun resolution. Concretely, a similarity cluster of delta phase between 350 and 700 msec after referent onset took place in a time window of 750–1100 msec postpronoun onset.

Word control RSAs between referent words yielded a trend-significance, delta-band phase pattern activation between 200 and 450 msec time-locked to referent word onset (Figure 2Aii; matching: cluster mean = 0.0136; nonmatching: cluster mean = 0.0097;  $p = .0879$ ). In addition, though, a trend-significance cluster where delta phase is more similar between nonmatching referent and pronoun words than between matching pairs was also found (Figure 2Aii;  $p = .0522$ ; matching: cluster mean = 0.0088; nonmatching: cluster mean = 0.0115); the cluster went between 600 and 1100 msec postreferent onset and between 550 and 750 msec postpronoun onset. No significant cluster was observed in the delta-band control RSA between pronoun words.

### Power

For the RSA between pronouns and referents, a significant cluster of similarities was again observed in delta-band power ( $p = .0270$ ; matching: cluster mean = 0.3180; nonmatching: cluster mean = 0.3142; Figure 2Bi), with neural activities between 750 and 1100 msec after referent onset activated throughout the period of 0–1300 msec postpronoun onset, likely also extending to the prestimulus period.

Between-referents word control RSAs showed a significant activation of delta-band power patterns underlying referent word processing. The peak of the cluster arose between 650 and 950 msec ( $p = .03$ ; matching: cluster mean = 0.3191; nonmatching: cluster mean = 0.3154; Figure 2Bii) and extended to later periods, sustaining until the end of the epoch period (i.e., 1.5 sec). No significant effect was observed in the word control RSAs between pronouns.

The RSA in delta power focusing on the prepronoun period showed a significant similarity cluster of delta power (matching: cluster mean = 0.3286; nonmatching: cluster mean = 0.3248,  $p = .0500$ ) between matching pronoun–referent word pairs compared with nonmatching pairs. The cluster goes on between 800 msec and 1100 msec postreferent onset and between –600 msec to 0 msec time-locked to pronoun onset, likely extending further to the postpronoun period and connected with our main pronoun–antecedent effect of delta power (see Figure 2Bi). For the figure showing the result, see Appendix 3.

The RSAs performed in the trial subset with two different baselines showed differing data patterns. No significant cluster was yielded when a baseline window of –0.3 to –0.1 sec was applied. In contrast, in the RSA with a baselining window of –1 to –0.8 sec, a significant negative cluster (i.e., matching < nonmatching) was identified (matching: mean cluster =  $-8.9091e-04$ , nonmatching:

mean cluster =  $2.0258e-04$ ;  $p = .0220$ ) and also a trend-significant negative cluster ( $p = .0669$ ). See Appendix 6 for the result figure.

### Theta Band (4–7 Hz)

#### Phase

In the pronoun–referent phase RSAs, a marginal but non-significant cluster where theta phase was more similar between mismatching referent and pronoun words than between matching word pairs was found (Figure 3Ai;  $p = .0508$ ; matching: cluster mean = 0.0737; nonmatching: cluster mean = 0.0708). Concretely, the cluster went between and 550 msec postreferent onset and predominantly between 350 and 700 msec postpronoun onset.

No significant effect was observed on the theta phase in word control RSAs between referent words (Figure 3Aii) or between pronoun words.

#### Power

The RSA between pronouns and referents yielded a trend-significance, referent-related, theta-band power activation, primarily between 200 and 300 msec after referent word onset and throughout the entire epoch (0–1500 msec) of pronouns ( $p = .0543$ ; matching: cluster mean = 0.2350; nonmatching: cluster mean = 0.2315; Figure 3Bi). The cluster might extend to the prestimulus and post-epoch periods time-locked to pronoun onset.

Between-referents word control RSAs show a trend-significance pattern activation of theta-band power underlying referent word processing. The peak of the cluster arises between 600 and 950 msec ( $p = .0942$ ; matching: cluster mean = 0.2926; nonmatching: cluster mean = 0.2892; Figure 3Bii). No significant effect is observed in the word control RSAs between pronouns.

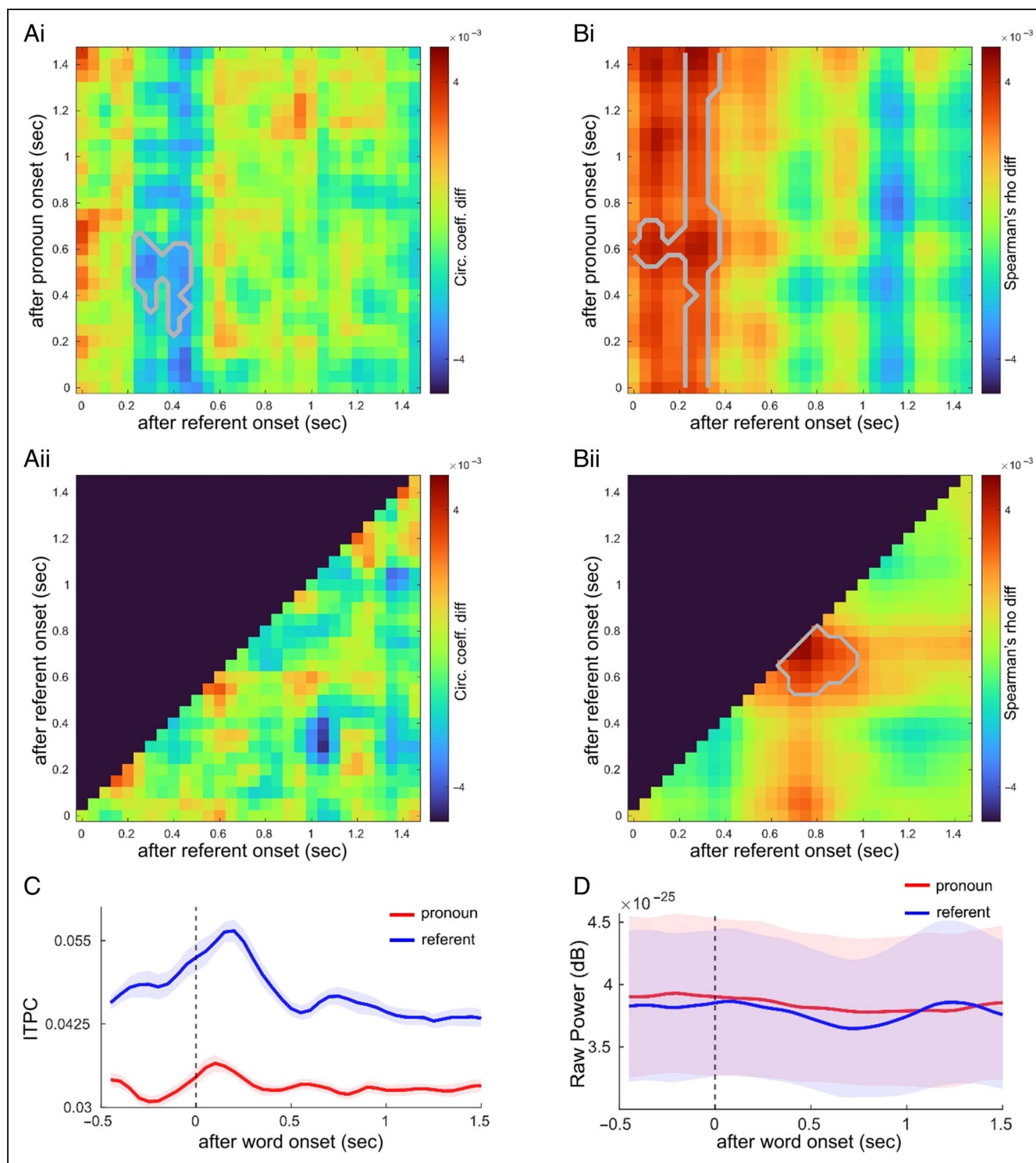
### Other Frequency Bands

No significant effect was found in any RSA in the alpha (8–12 Hz), beta (13–20 Hz), or low-gamma (35–80 Hz) band.

### POS Analysis

Our analysis of POS variability surrounding pronouns (see Appendix 5) shows that approximately 33.6% of the pronouns were immediately preceded by verbs and conjunctions, more often than other word positions around pronoun onset. In the POS variability analysis, no evident difference in the proportion of each primary word class (e.g., verb, auxiliary verb, conjunction, adposition, adjective, adverb, noun, pronoun, determiner) before and after pronoun onset (except the two positions immediately close to pronouns) was observed, nor between referent nouns and pronouns.





**Figure 3.** Similarity of referent-related theta-band (4–7 Hz) activities during pronoun resolution. (A) Temporal generalization maps averaged across participants for theta phase. (i) Averaged temporal generalization map for the difference between matching and nonmatching pronoun–referent word pair conditions. (ii) Averaged temporal generalization map for the difference between formally identical and non-identical word pair conditions. Regions highlighted with gray outlines indicate trend-significant difference at the  $p = .05$  level. (B) Similarity of neural representations of referent words is found in theta-band power during pronoun resolution. (i) Averaged temporal generalization map for the difference between matching and nonmatching pronoun–referent word pair conditions. (ii) Averaged temporal generalization map for the difference between formally identical and non-identical word pair conditions. Regions highlighted with gray outlines indicate trend-significant difference at the  $p = .05$  level. (C) Uncorrected, mean ITPC averaged per temporal channel per theta frequency. The ITPCs of pronoun and referent trials were plotted as separate lines. Note that the higher ITPC for referent words here could be because of the fact that the number of referent word trials are smaller than that of pronoun word trials. (D) Mean theta power across the delta band and across all temporal channels. The mean power of pronoun and referent trials was plotted as separate lines. Shaded error bars indicate the standard error of the mean.

## Acoustic RSA

By visual inspection, we did not find any similarity pattern in the acoustic RSA generalization map that matches our neural similarity effect between pronouns and referents. Specifically, most of the referent–pronoun acoustic RSA showed rather a negative trend for RSA, whereas we find positive power similarity effects in delta and theta. For the acoustic RSA on identical referent noun words, some acoustic similarity was found before word onset, but the timing was earlier than for the delta effect (see Appendix 4).

## DISCUSSION

When we understand a pronoun in a phrase, sentence, discourse, or story, the brain accesses matching entities or concepts that have been encoded in memory from the previously presented linguistic context. Recent advances in the neurobiology of memory point to a mechanistic account of memory retrieval wherein memory traces are (re)activated via the reinstatement of oscillatory neural representation underlying encoding (e.g., Johnson & Rugg, 2007). Meanwhile, in a cue-based account of language processing (e.g., Martin, 2016, 2020), it is proposed that, during pronoun resolution, the brain takes as its input exogenous cues (e.g., sensory features) and accesses via those external cues previously encoded, internal representations of entities that match the current pronoun, so that the resolution of a pronoun is accomplished (Parker, 2019; Foraker & McElree, 2007; LeDoux et al., 2007). Importantly, in line with the findings of oscillatory dynamics reinstatement in memory retrieval, the account also asserts that internal linguistic elements can be represented by (a)synchronously firing neuronal ensembles. We hypothesized that retrieving previously encoded antecedents engages the reinstatement of oscillatory neural dynamics as well during pronoun resolution. Here, we leveraged neural decoding techniques (i.e., RSA) on MEG data acquired during a naturalistic story listening task. We found that delta-band (and potentially also theta-band) power and phase during pronoun resolution in ongoing spoken language comprehension was similar to activity during processing of its antecedent. Our findings suggest that the brain may retrieve a referent by some form of reinstatement of its rhythmic neural representation. Interestingly, in our delta power effects, the similarity also occurred before pronoun onset, suggesting that the predictive status of stimulus context likely interacts with reinstatement of memory representations. Our attempt to observe evidence using decoding techniques (i.e., RSA) bridges the gap between two burgeoning, oscillation-based accounts of language processing and memory, that is, cue-based memory retrieval and reinstatement of oscillatory dynamics in the brain.

We assessed whether oscillatory activity underlying referent processing was reinstated during pronoun

resolution in a strict sense: We took particular interest in delta-band (1–3 Hz) activity as it has been shown to concern processing of higher-order, meaningful linguistic components such as words and phrases (e.g., Attaheri et al., 2022; Bai et al., 2022; Coopmans et al., 2022; Lo, Tung, Ke, & Brennan, 2022; Ten Oever et al., 2022; Henke & Meyer, 2021; Kaufeld et al., 2020; Weissbart, Kandylaki, & Reichenbach, 2020; Brennan & Martin, 2020; Keitel, Gross, & Kayser, 2018; Molinaro & Lizarazu, 2018; Meyer et al., 2017; Molinaro, Lizarazu, Lallier, Bourguignon, & Carreiras, 2016; see Meyer, 2018, for a review). Critically, we captured strong effects of similarity over both the phase and power of antecedent-related delta-band responses during pronoun word processing, suggesting that delta-band dynamics may be involved as a mechanism that enables the brain to retrieve and represent an antecedent during language comprehension. Previous ERP results on the neural processing of reference have provided compelling supportive evidence for the cue-based account by showing that retrieving internal linguistic knowledge can be interfered by processing referentially incoherent or ambiguous input (e.g., Coopmans & Nieuwland, 2020; Karimi et al., 2018; Nieuwland, 2014; Nieuwland & Van Berkum, 2008). However, the current study takes an important first step further to characterize how such internal, abstract linguistic concept representations may be retrieved and involved in spoken language processing, namely, via the enhanced activation of referent-related delta range patterns. On this note, our results also add to prior evidence supporting the cue-based account and suggest that generation of linguistic elements is achieved via (a)synchronously firing of neuronal ensembles.

Note that it is hard to conclude that our observed effect was solely because of reinstatement of antecedent-related activity by the presentation of pronouns, as our additional results (see Appendix 3) showed that the similarity in delta power between pronoun- and referent-related activity was already present during the prepronoun period. One might be tempted to conclude that these effects are because of lingering antecedent activation from other parts of the discourse because of antecedent or pronoun properties. However, we believe this is unlikely considering our analytic approach. First, the same set of antecedents were used, that is, their neural correlates were correlated with those of pronouns to generate datapoints of both matching and nonmatching categories. Therefore, the activation of an antecedent affects not only the results of matching antecedent–pronoun pairs but, importantly, those of nonmatching pairs as well. In this case, even if an antecedent is activated persistent, its lingering activation will be captured by both matching and nonmatching pronouns. Also crucially, to prevent the confound of neural similarity caused by closer temporal proximity between (non-) matching word pairs in general, we kept the averaged temporal distance (here specifically, the median word

distance) between matching and nonmatching antecedent-pronoun pairs constant. Controlling for temporal distance ensures that any effect that would be because of lingering activation (or autocorrelations that are stronger for nearby signals) is the same in the matching and nonmatching pairs. Hence, although given the current findings that it is hard to maintain that the presentation of the referent is the deciding factor of the reinstatement of the content, we believe it can still be concluded that during the discourse of sentence processing around the pronoun, neural representations that reflect the representation of pronoun are activated.

Moreover, we believe this prepronoun similarity finding fits into emerging theoretical perspectives of language comprehension (predictive processing; e.g., Kutas, DeLong, & Smith, 2011) and communication (efficiency; e.g., Piantadosi, Tily, & Gibson, 2012). Referent-related activation before the presentation of a pronoun could be explained by predictive activation of antecedent concepts by incoming local syntactic constructions (e.g., verb phrases where a pronoun is usually embedded), which is not unlikely considering the predictive nature of language processing (e.g., see Ryskin & Nieuwland, 2023; Nieuwland, 2019; Kutas et al., 2011). Previous findings have demonstrated that supportive discourse, and thus prediction (Ryskin & Nieuwland, 2023; Nieuwland, Arkhipova, & Rodríguez-Gómez, 2020; Nieuwland, 2019), enable referential processing to go beyond the constraints of lexical association or feature matching. In a naturalistic discourse, which is both supportive and coherent, animate pronouns (e.g., *s/he*) can refer to inanimate objects (e.g., *nuts*) when the discourse imbues them with information such that they can be retrieved, for example, when the inanimate objects are characters in a story where a peanut and an almond fall in love (Nieuwland & Van Berkum, 2006). Thus, it is highly likely that the brain is using discourse context to predict what is going to be referred to (Carter & Nieuwland, 2022; Nieuwland, Otten, & Van Berkum, 2007). Besides, in keeping with the account of communication efficiency that word lengths are optimized for efficient communication in context, converging evidence has shown that writers use more pronouns than full noun-phrases to represent an antecedent when the antecedent concept is perceived by the reader as predictable in a given sentential context (e.g., Rosa & Arnold, 2017; Tily & Piantadosi, 2009). In other words, pronouns in natural discourses tend to occur frequently where referential concepts are more predictable, or say easily accessible during cognitive processing. Altogether, our results, which do not strongly distinguish between onset and offset of the pronoun's acoustic realization, are consistent with this literature.

Our present results also speak to the emerging neurobiological account of memory processes in which neural patterns during encoding are reinstated at retrieval (e.g., Ten Oever et al., 2021; Pacheco Estefan et al., 2019; Staresina et al., 2019; Jang et al., 2017; Xiao et al., 2017; Yaffe et al., 2017; Manning et al., 2012; Johnson & Rugg, 2007). It has

been proposed that, during encoding of an experience, both externally perceived and internally generated aspects of the experience are processed by sensory and association cortical areas (e.g., lateral and medial temporal lobes) and then integrated into a cohesive memory via the hippocampus (Preston & Eichenbaum, 2013; Mayes, Montaldi, & Migo, 2007). According to this proposal, to successfully access stored memory traces and re-experience the event, the brain has to reinstate relevant cortical activities (e.g., Jang et al., 2017; Preston & Eichenbaum, 2013; Sederberg et al., 2007). In support of the proposal, multiple recent studies have shown that the recall of an event involves reinstatement of oscillatory brain activity that occur during the encoding of the experience of the event (Ten Oever et al., 2021; Staresina et al., 2019; Yaffe et al., 2017). Pronoun resolution, in its essence, should be largely categorized as a memory retrieval process (see Foraker & McElree, 2007; McElree, 2006), as representations of a previously encoded antecedent would always have to be recovered based on sensory input of a pronoun. Our current findings do not indicate that pronouns exclusively reinstated referent-related activity, but rather suggest an active role for prediction before the onset of pronouns. Although our results are in line with prior findings that lower-frequency bands (e.g., theta) can be engaged in memory trace reinstatement, we did not observe any effect in the gamma range, which in contrast has been repeatedly found in the memory literature (e.g., Ten Oever et al., 2021; Staresina et al., 2019; Yaffe et al., 2017; Yaffe et al., 2014). This could have been because of the general low signal-to-noise ratio in gamma-band activity that makes it difficult to disentangle the gamma effect(s) from non-neural noise (e.g., muscle artifacts). It could also be the case that temporal alignment was not identical across trials, which had made correlations between gamma responses less distinguishable given the transiency of its cycles. Taken together, the current study moves one step forward to bridge emerging, neural-oscillation-based theories of language and of memory in the brain that have long been studied separately. Future studies on language processing could further examine whether oscillatory neural (especially delta) pattern enhancement/reinstatement also underlies other types of long-distance dependency resolution such as ellipsis or displacement arising from movement operations (e.g., *wh*-question construction in English), or even word composition in phrasal building.

Our findings also converge with the previous studies that show the involvement of delta-band activity in processing of higher-order, meaningful linguistic elements (e.g., Bai et al., 2022; Coopmans et al., 2022; Ten Oever et al., 2022; Henke & Meyer, 2021; van Bree et al., 2021; Brennan & Martin, 2020; Kaufeld et al., 2020; Ríos-López, Molinaro, Bourguignon, & Lallier, 2020; Meyer et al., 2017; Ding et al., 2016). However, earlier findings have not disentangled two potential processes that can involve the delta range, that is, an intrinsic slower temporal



constraint for the tracking of higher-order linguistic components from external speech streams (e.g., Lakatos et al., 2019; Rimmele et al., 2018) or a functional pattern that facilitates the generation of abstract linguistic representations (e.g., Meyer et al., 2020). Our results corroborate previous findings by showing that the delta frequency range is involved in the processing of higher-level linguistic representations (i.e., referential meaning). More importantly, the current study goes one step further to show specifically that delta-band responses are engaged in the generation of top-down linguistic representations via activation of information carried in phase and power, as referential meaning cannot be immediately “tracked” from the speech envelope but needs to be inferred based on internal knowledge and external input. We have to note, though, that our results do not rule out the possibility that delta activity is also involved in tracking higher-level linguistic input, as both phase and power patterns were also found between identical words at relatively earlier periods of processing than the time window of referential meaning retrieval. However, it is at least clear from the current study that the delta band does more than mere tracking, as recovering internally stored linguistic concepts is required for the brain to process a pronoun. This view is consolidated by our acoustics RSA between pronouns and referents in which we found no increased similarity between the acoustics of matching pronoun–referent pairs. Our findings for pronoun–referent RSA results in delta/theta power thus cannot be explained by acoustically driven similarities between pronouns and referent nouns, and support the hypothesis that the delta effect and the theta trend-effect stem from internal cues, that is, abstract linguistic components. Besides, differing patterns were identified in the present study between delta and theta, the frequency band that has been repeatedly found associated with syllable processing (e.g., Poeppel & Assaneo, 2020; Kösem et al., 2018; Ten Oever & Sack, 2015; Giraud & Poeppel, 2012; Luo & Poeppel, 2007)—namely, that robust modulations of delta were observed during the resolution of a pronoun, but not of theta, although pronouns are more often theta-sized than delta-sized. Concretely, we found that the time window of theta power reinstatement in referent words predominantly lasted from 200 to 350 msec poststimulus onset, whereas delta power reinstatement happened much later after referent word onset (i.e., 750–1100 msec; see Figures 2Bi and 3Bi). Such a distinction indicates that the delta frequency range tends to be engaged differently in spoken language processing than theta—that is, although theta may reflect early-period memory operations on speech streams such as syllable and word recognition, delta may be more closely involved in later processes, that is, retrieval of more abstract linguistic representations (e.g., stored lexical information, knowledge of grammar, semantic memory, event representations, conceptual information). Our current findings provide empirical evidence to disentangle the role of delta activity in accessing internally stored linguistic representations

from tracking external input during spoken language comprehension.

Zooming in to the current findings, intriguingly results of control analyses on antecedent words showed a consistent temporal relationship with the pronoun–referent results in both delta phase and power. For delta phase, the similarity effect, which likely suggests referential meaning retrieval, was identified between 350 and 700 msec after referent onset. Meanwhile, control RSAs between antecedent words yielded an earlier, trend-significance delta-band phase pattern activation between 200 and 450 msec time-locked to antecedent word onset. At first, it seemed puzzling that the delta phase effect seemed rather weak (only trend-significant) as it concerns matching nouns. However, in ongoing speech, words are always embedded in a bigger context and not pronounced identical (e.g., Kleinschmidt, 2019). This lack of acoustic similarity of identical referent nouns (after word onset) was confirmed by our acoustic RSA. In the delta phase effect identified between pronouns and referents, the time window time-locked to referent nouns was found to match the time window of the N400 ERP effect, which has been suggested to be associated with processing at the lexical level (e.g., lexico-semantic, phonological; Ito, Corley, Pickering, Martin, & Nieuwland, 2016; Frank, Otten, Galli, & Vigliocco, 2015; DeLong, Urbach, & Kutas, 2005; Van Berkum, Brown, Zwitterlood, Kooijman, & Hagoort, 2005; Kutas & Hillyard, 1984). Therefore, this indicates that, for referent words, (pre-)lexical processing takes place earlier than referential meaning retrieval in referents. This is convergent with prior findings suggesting a sequential model that referential resolution follows lexical activation (e.g., Coopmans & Nieuwland, 2020; Brodbeck et al., 2016).

It is also interesting to note that, although the intertrial phase coherence (ITPC) of delta activity was clearly distinct between pronoun and referent trials, the mean power seemed to stay highly similar (see Figure 2C and D). The higher ITPC in referents than pronouns could be because of the fact that referent trials are smaller in number. However, the discrepancy between ITPC and power indicates that phase measures can be more sensitive to conditional contrasts (e.g., adjusts more transiently to sensory input) than power in naturalistic experimental setups. Taken together, these results provide compelling evidence that delta-band activity is involved in late, post-lexical construction of referential meaning during pronoun resolution, more importantly via involvement as referent-related neural representation. This is also consistent with the cue-based account of language processing that claims that internally stored linguistic cues guide linguistic structure generation in slower neural responses such as delta (Martin, 2020).

In our study, we did not perform baseline correction, which is normal in typical ERP approaches (e.g., Alday, 2019). Performing baseline correction on naturalistic data has the problem of potentially introducing prestimulus

effects into the poststimulus window. This is even more evident considering that we found prestimulus effects in our delta power RSA. In this situation, performing baseline correction could mask or even inverse our reported effects. Therefore, not performing baseline correction is likely the best approach. One valuable point of our current study is to characterize antecedent-related activity during pronoun resolution during a naturalistic spoken language listening setting. Although not being able to causally capture the role(s) of neural dynamics as naturalistic data can be noisy in contrast to those collected from strict experimental controls—which is illustrated by the issue of baseline-correcting—the data-driven approach based on naturalistic tasks, for example, the decoding technique we applied here, can provide valuable information about naturalistic language processing and thus spark hypotheses for emerging theories and future experimental studies.

Our results are important to relate to previous ERPs findings about referential processing. The Nref, related to pronoun resolution, has been reported between 300 and 1500 msec (e.g., Coopmans & Nieuwland, 2020; Nieuwland et al., 2019; Nieuwland & Van Berkum, 2008). Meanwhile, the late positivity component, which typically lasts between 600 and 900 msec, has been long established in ERP literature to be relevant to lexical meaning processing (e.g., Coopmans & Nieuwland, 2020; Kolk & Chwilla, 2007). The delta power similarity cluster that we observed is therefore consistent with the identified ERP time windows for pronoun and referent processing. It is likely that our current results are associated or even overlap with some of these ERP responses. However, typically, the Nref is achieved from data sets with specific experimental setups, that is, pronouns that do not match their referent (perfectly) in a pair of short sentences. It is difficult to directly compare this to the responses in our naturalistic data set in which the pronoun always matches the referent. Even if our component would relate to the Nref, our study provides a more nuanced view of pronoun processing as so far, the identified Nref component has not been shown to be item-specific (i.e., representing a specific pronoun or referent entity). The current Nref findings could therefore simply relate to contextually problematic pronouns in general (e.g., incoherent or ambiguous). In contrast, our current findings suggest the variation of delta activity is involved in representation of each single referent.

It is still worth pointing out that the exact functional role delta activity plays in neural representation of reference remains an open question. Pronoun resolution is

inherently difficult to separate from other cognitive processes associated with building or updating the situation model of a discourse, which includes for instance integration of referential entities to the event where they are embedded, or encoding of new features into entity representation. Therefore, it is possible that the observed delta-band reinstatement does not precisely reflect the representation of any individual referential concept in isolation, but a more dynamic process that involves relational concept representation. One potential alternative interpretation is that delta reinstatement reflects a referential entity-specific binding process where the entity is integrated with its predicate or broader sentential context as an argument (as in Martin & Doumas, 2017; see Martin & Doumas, 2019, for a review). Another way to look at the delta reinstatement effect is that previously encoded features of an entity may be synchronously replayed in delta cycles so that the features are subject to interference by incoming novel information. Although there is as of yet little empirical evidence showing the involvement of delta activity in memory replay during the awakening state (see, e.g., Girardeau & Lopes-Dos-Santos, 2021, for a review on delta replay during sleep), slower oscillations such as theta in the hippocampus have long been found to be associated with episodic memory formation and consolidation (e.g., Lisman & Jensen, 2013; Jensen & Lisman, 2005). Meanwhile, it has also been suggested that hippocampal theta oscillations tend to be slower in humans, that is, fall into 1–4 Hz, the frequency range usually named as delta (e.g., Jacobs, 2014). It is therefore reasonable to speculate that delta activity could also be engaged in memory formation. Our data cannot distinguish between these possibilities. We invite future research to investigate the functional role of the delta frequency range in the process of pronoun resolution more closely.

In summary, by bridging burgeoning, brain oscillation-based accounts of language processing and memory, our findings provide new insight into the neurobiological substrates of referent representation and pronoun resolution. We show that establishing reference involves neural patterns that first occurred during the processing of the antecedent word, possibly in a predictive fashion, but, in particular, occurring in the delta band. Our data thus suggest that, during spoken language comprehension, processing that calls upon internally stored linguistic representations to create meanings (here, referential dependencies) may require some degree of reinstatement of the oscillatory brain responses that occurred when those stored representations were first encountered.

## APPENDIX 1

See the table below for a comprehensive view of the number of participants and trials in each language comprehension study using RSA.

**Table A1.** Number of Participants and Trials in RSA Studies of Language Comprehension

<i>Study</i>	<i>Number of Participants</i>	<i>Number of Trials</i>
Wang et al. (2020)	32	700 (404 animate-constraining, 396 inanimate-constraining)
Tyler et al. (2013)	13	175 (1/3 unambiguous, 2/3 ambiguous)
Hultén et al. (2021)	20	118 (59 concrete words, 59 abstract words)
Giari et al. (2020)	25	160 (per category) × 5 word categories = 800
Wang et al. (2018)	26	240 (120 high predictability, 120 low)
Klimovich-Gray et al. (2019)	20 (but 4 participants were excluded)	154 (noun phrases)
Klimovich-Gray et al. (2021)	24	80 per condition × 4 conditions = 320 (words)

## APPENDIX 2 ILLUSTRATION OF WORD STIMULUS SELECTION AND PAIRING IN RSA

See a discourse example (AN = antecedent noun; P = pronoun):

“The ugly **duckling** (AN1) came to the big swamp where the wild **ducks** (AN2) lived. Here **it** (P1; the ugly duckling) lay all night; **it** (P2; the ugly duckling) was tired and sad. Next morning the wild **ducks** (AN3) flew over and took a look at **their** (P3; the wild ducks) new comrade.... The **duckling** (AN4; the ugly duckling) turned in all directions and greeted as kindly as **it** (P4; the ugly duckling) could.”

From the example, we can select four antecedent nouns (AN1, AN2, AN3, and AN4) and 4 pronouns (P1, P2, P3, and P4), and we thus create the following matching and nonmatching antecedent–pronoun word pairs:

Matching pairs: AN1-P1, AN1-P4, AN2-P2, AN2-P3, AN3-P2, AN3-P3, AN4-P1, AN4-P4.

Nonmatching pairs: AN1-P2, AN1-P3, AN2-P1, AN2-P4, AN3-P1, AN3-P4, AN4-P2, AN4-P3.

Then, correlations between antecedents and pronouns are performed and two conditions are contrasted based on

the pairing above. In the two conditions, the instances of antecedents and pronouns we include and their number of occurrences are:

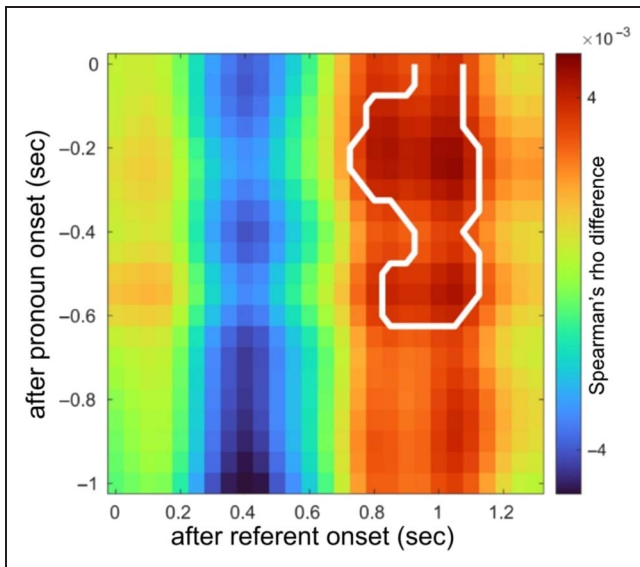
**Table A2.** Number of Instances of Each Stimulus Word per Condition

<i>Matching Condition</i>	<i>Nonmatching Condition</i>
AN1: 2	AN1: 2
AN2: 2	AN2: 2
AN3: 2	AN3: 2
AN4: 2	AN4: 2
P1: 2	P1: 2
P2: 2	P2: 2
P3: 2	P3: 2
P4: 2	P4: 2

Therefore, by employing the RSA method illustrated above, noun and pronoun trials in their respective correlation will always be in both matching and nonmatching conditions and the proportions will always be the same. Note, however, that the nonmatching condition typically does have many more pairs, but in the same proportion as in the matching condition.

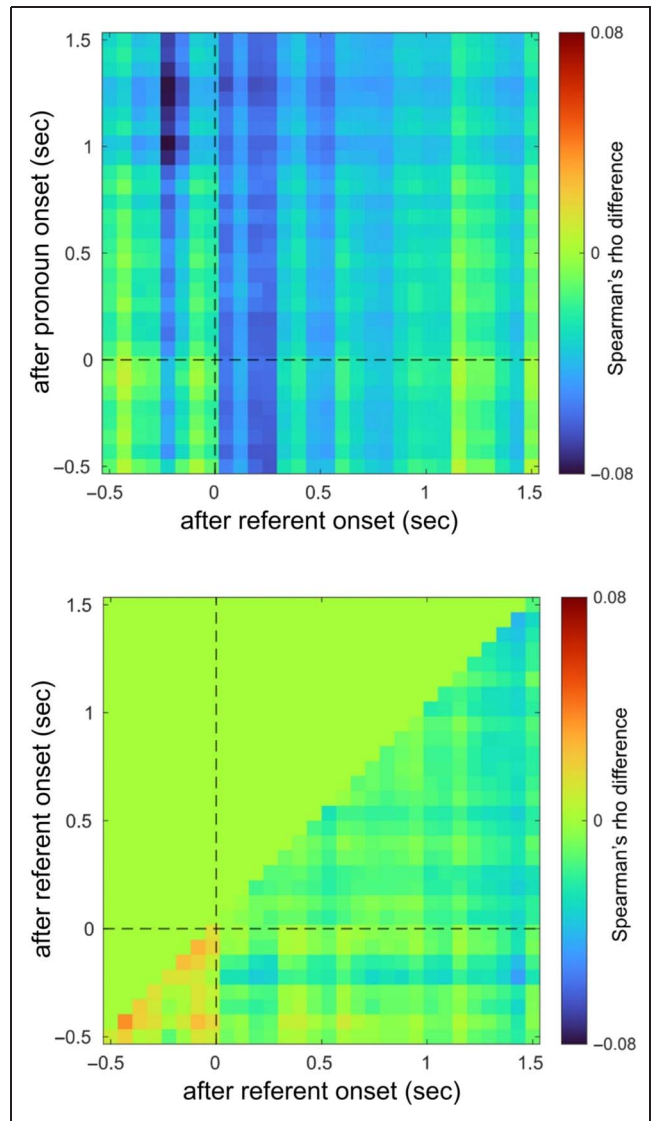


**APPENDIX 3 REFERENT-RELATED, DELTA-POWER ACTIVITY IN THE PREPRONOUN PERIOD**



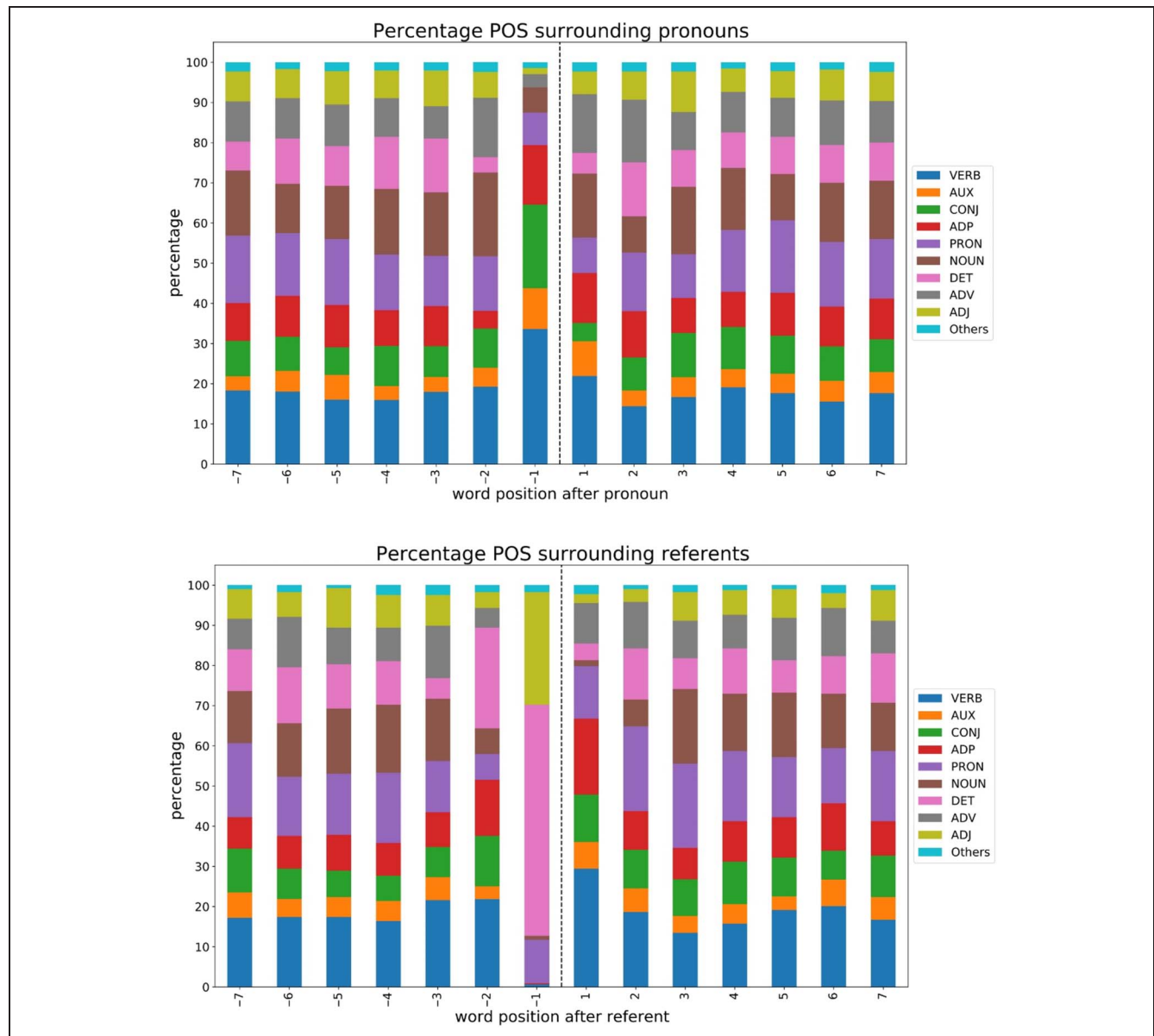
**Figure A3.** Temporal generalization map averaged across participants for the difference between matching and nonmatching pronoun-referent word pair conditions, focused on the prepronoun onset period. Regions highlighted with white outlines indicate significant difference at the  $p = .05$  level.

**APPENDIX 4 ACOUSTIC RSA BETWEEN PRONOUNS AND REFERENTS: RESULTS**



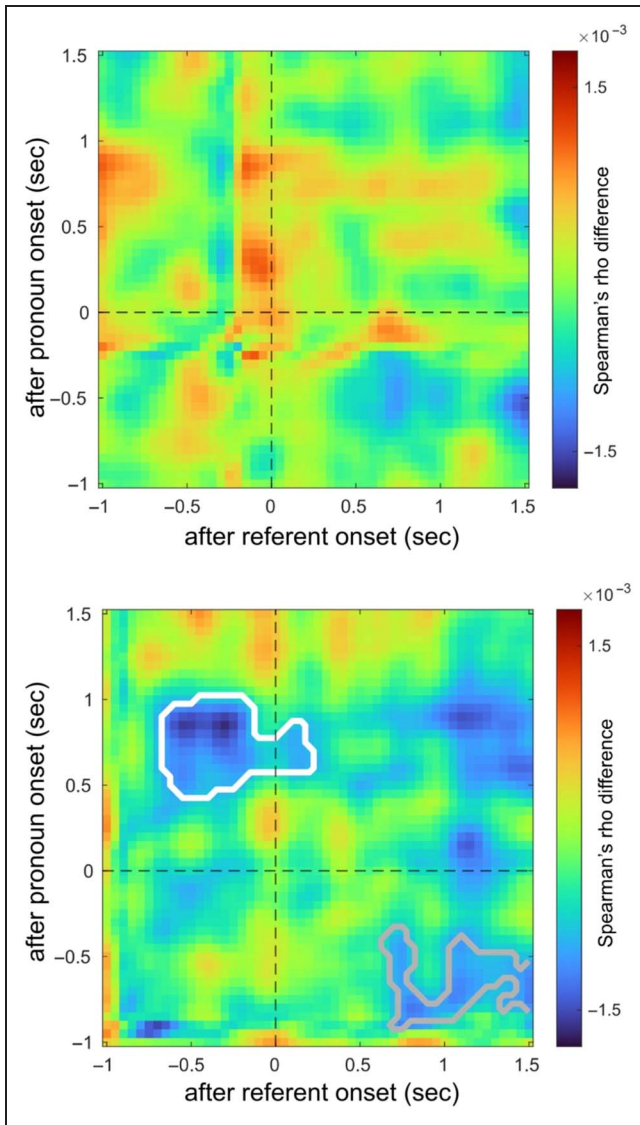
**Figure A4.** Temporal generalization map for the difference between matching and nonmatching pronoun-referent word pair conditions (above) and identical and non-identical referent words (under) in their spectrograms.

## APPENDIX 5 POS VARIABILITY SURROUNDING TARGET WORD STIMULI



**Figure A5.** POS variability metrics of seven preceding and following word positions surrounding pronouns and referent nouns. Different colors indicate different word categories/classes. VERB = verbs; AUX = auxiliary verbs; CONJ = conjunctions, subordinating (e.g., if, while) and coordinating (e.g., and, or, but); ADP = prepositions and postpositions (e.g., in, to); PRON = pronouns in a general sense, including personal, reflexive, interrogative, relative, indefinite, total, negative, possessive, and attributive; NOUN = nouns; DET = determiners; ADV = adverbs; ADJ = adjectives; Others = PROPN (proper nouns) + INTJ (interjective) + NUM (numbers) + PUNCT (punctuations) + X (words that cannot be categorized, missing values).

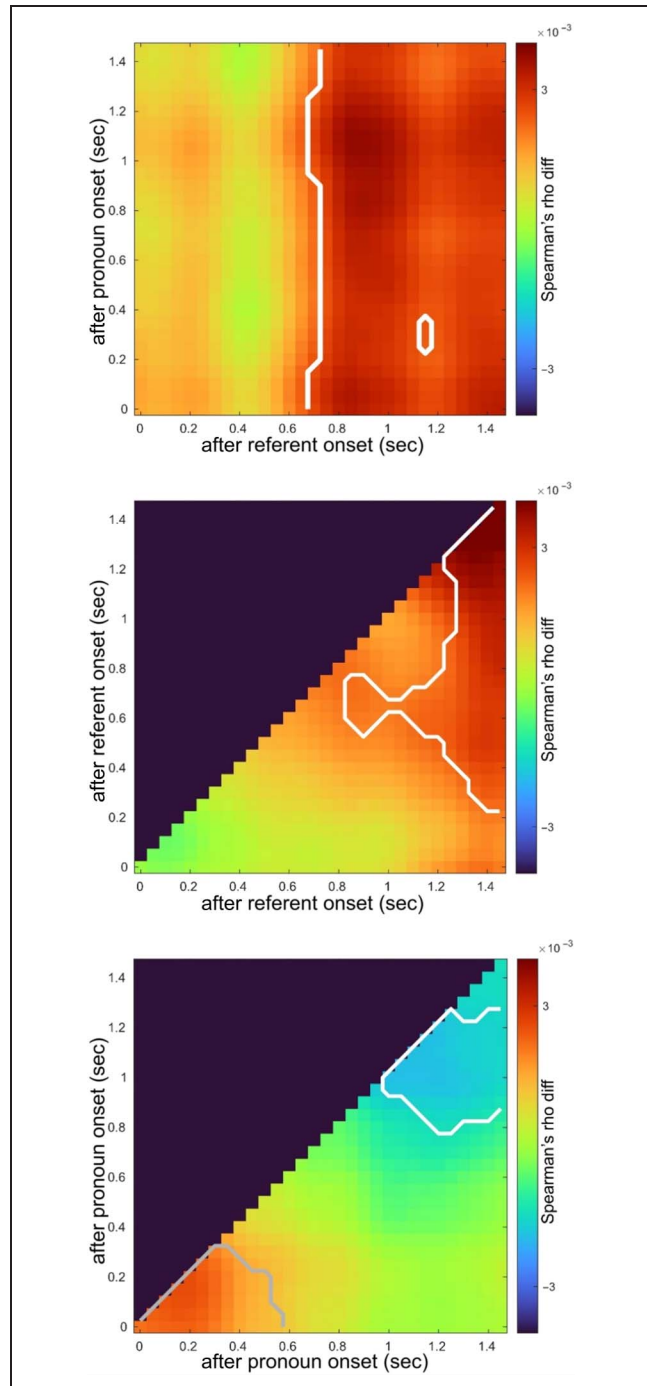
**APPENDIX 6 BASELINE-CORRECTED ANTECEDENT-PRONOUN RSA RESULTS ON A TRIAL SUBSET**



**Figure A6.** Temporal generalization maps averaged across participants for the difference between matching and nonmatching pronoun-referent word pair conditions, with a baseline window of  $-0.3$  to  $-0.1$  sec (above) and  $-1$  to  $-0.8$  sec (below). Regions highlighted with white outlines indicate significant difference at the  $p = .05$  level, whereas those highlighted in gray indicate trend-significant difference.

**APPENDIX 7 SENSOR-LEVEL RSA RESULTS IN THE DELTA BAND ACROSS ALL CHANNELS**

Across all MEG channels, the RSA in delta-band activity yielded a significant cluster of similarity in delta-band power ( $p = .012$ ; Figure A7A), but not in the delta phase. Word control RSAs between referent words yielded a significant delta-band power pattern activation (Figure A7B;  $p = .0225$ ). The control RSA between pronoun words showed a trend-significant pattern activation cluster (Figure A7C;  $p = .0519$ ) and a significant pattern de-activation cluster ( $p = .0478$ ).



**Figure A7.** Similarity of delta-band (1–3 Hz) power during pronoun resolution across all MEG channels. (A) Temporal generalization map averaged across participants for the difference between matching and nonmatching pronoun-referent word pair conditions. Regions highlighted with white outlines indicate significant difference at the  $p = .05$  level, whereas those highlighted in gray indicate trend-significant difference. (B) Temporal generalization map for the difference between formally identical and non-identical referent word pair conditions. (C) Temporal generalization map for the difference between formally identical and non-identical pronoun word pair conditions.



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### Data Availability Statement

Preprocessed data and relevant analysis pipelines are available at the Donders Data Repository (<https://doi.org/10.34973/ybzy-4390>). Stimulus annotations are available at a Github repository: [https://github.com/lacns/Dingetal\\_2024\\_JCoN](https://github.com/lacns/Dingetal_2024_JCoN). Raw data are available as another collection at the Donders Data Repository (<https://dx.doi.org/10.13039/501100003246>).

### Funding Information

A. E. M. was supported by an Independent Max Planck Research Group and a Lise Meitner Research Group “Language and Computation in Neural Systems” from the Max Planck Society, by the Netherlands Organization for Scientific Research (NWO; grant 016.Vidi.188.029) (<https://dx.doi.org/10.13039/501100003246>), and by Big Question 5 (to Prof. Dr. Roshan Cools & Dr. Andrea E. Martin) of the Language in Interaction Consortium funded by an NWO Gravitation Grant (024.001.006) awarded to Prof. Dr. Peter Hagoort. SO was also supported by the European Research Council (ERC-2023-STG; 101116685) and by the Dutch Research Council (NWO; Starter Grant awarded to starting assistant professors).

### Diversity in Citation Practices

Retrospective analysis of the citations in every article published in this journal from 2010 to 2021 reveals a persistent pattern of gender imbalance: Although the proportions of authorship teams (categorized by estimated gender identification of first author/last author) publishing in the *Journal of Cognitive Neuroscience (JoCN)* during this period were  $M(\text{an})/M = .407$ ,  $W(\text{oman})/M = .32$ ,  $M/W = .115$ , and  $W/W = .159$ , the comparable proportions for the articles that these authorship teams cited were  $M/M = .549$ ,  $W/M = .257$ ,  $M/W = .109$ , and  $W/W = .085$  (Postle and Fulvio, *JoCN*, 34:1, pp. 1–3). Consequently, *JoCN* encourages all authors to consider gender balance explicitly when selecting which articles to cite and gives them the opportunity to report their article’s gender citation balance.

### Notes

1. Our sample size is expected to capture the hypothesized similarity effect given findings of prior language comprehension studies performing RSA on MEG data (Hultén et al., 2019, 2021; Giari et al., 2020; Wang et al., 2018, 2020; Klimovich-Gray et al., 2019; Tyler et al., 2013). Previous language comprehension studies that observed significant effects by conducting RSA on MEG data have collected participants varying from 10 to 74 in number (median = 24). Most crucially for the planned RSA analysis, our study included 1198 trials (791 pronouns and 407 referent nouns), which is more substantial than the

standard number of trials in the existing literature. For a comprehensive view of the number of participants and trials in each language comprehension study using RSA, see the table in Appendix 1. We note that none of these previous instances used ongoing speech.

2. We have also conducted RSA in the delta band across all MEG channels. This was to help understand our null results in the source space. All the other parts of the method, including the cluster-based statistics (to be mentioned below), remained the same as the original RSA. See Appendix 7 for results.

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