Alpha and beta desynchronization during consolidation of newly learned words

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Running head: alpha-beta desynchronization during covert production of newly learned words

Abstract

While a growing body of literature exists on initial word-to-meaning mapping and retrieval of fully lexicalized words, our understanding on the learning of semantic knowledge that occurs between these two stages remains limited. The current study investigated the neural correlates of retrieving newly learned word meanings using oscillatory brain dynamics. Participants learned to associate new words with unknown objects and performed overt and covert naming tasks during the first and last days of a five-day training period. Behavioral results showed improved overt naming on Day 5 compared to Day 1. Selecting only words that were successfully produced in the overt naming task, we examined alpha (8-12 Hz) and beta (13-25 Hz) band oscillatory activity associated with lexical-semantic retrieval while participants produced new words covertly, both pre- (Day 1) and post (Day 5) lexicalization. The results showed a robust alpha and lower beta power decrease during covert naming after learning. We hypothesize that this alpha-beta power decrease indexes successful word retrieval following lexical-semantic integration and consolidation.

Introduction

Associating novel verbal labels to referents is a core learning mechanism essential for language acquisition. Following initial word-referent mapping, new lexical candidates eventually become integrated into existing semantic networks, allowing us to retrieve words from memory during language comprehension and production. Several studies have shown rapid cortical changes after very little exposure to lexical items in sentential context (Batterink & Neville, 2011; Borovsky et al., 2010; Lemhófer et al., 2025; Mestres-Missé et al., 2007; Perfetti et al., 2005; Shtyrov et al., 2010), which is sometimes interpreted as indexing new lexical entries (Gaskell & Dumay, 2003). However, it is a matter of debate whether these words have entered learners' lexical-semantic network or whether they are temporarily associated with known concepts (for different perspectives, see Tamminen & Gaskell, 2013 or Rodriguez-Fornells et al., 2009). Indeed, it has been argued that lexicalization, or the integration of new items into a speaker's existing lexicon, only occurs after a period of consolidation (Bakker et al., 2015; Davis & Gaskell, 2009; Kaczer et al., 2018; Korochkina et al., 2024; Hulme & Rodd, 2023; Liu & van Hell, 2020; Schimke et al., 2022; Tamminen & Gaskell, 2013 but see Mestres-Misse et al., 2007 for a different perspective). Despite a growing body of studies examining either initial word encoding or the semantic processing of fully integrated words, little is known about the semantic processes occurring between initial word-to-meaning mapping and full lexicalization. The current study focused on this phase by exploring the neural correlates of retrieving newly learned lexical items.

Within the framework of predictive language processing, decreased power or desynchronization in the alpha (8-12 Hz) and beta (13-25 Hz) frequency bands is thought to index linguistic prediction so that, preceding the word's appearance, it is greater for both new words and real words in highly constraining sentences, relative to less constraining ones (Momsen & Abel, 2022; Wang, Hagoort, & Jensen, 2018). This pattern of oscillatory activity has been noted in both written and spoken language comprehension studies (León-Cabrera et al., 2022) and both for comprehension and production (Gastaldon et al., 2020), and it is most probably related to retrieving lexical-semantic representations. Both alpha and beta decreases are considered to index semantic memory retrieval (Hanslmayr et al., 2012; Klimesch, 1999), including lexical-semantic retrieval (Branzi et al., 2023; Piai et al., 2015; Piai & Zheng, 2019; Hubbard and Federmeier, 2004). However, inconsistencies remain regarding as to whether beta (Bakker et al., 2015; Bastiaansen et al., 2005; Momsen et al., 2002), alpha (León-Cabrera et al., 2022; Strauß et al., 2014; Lago et al., 2023) or both frequency bands (Gastaldon et al., 2020; Hustá et al., 2021; Klimesch et al., 2001; Momsen & Abel, 2022; Piai et al., 2015) underlie these semantic-related processes.

Concerning word learning, only one previous oscillatory study examined the lexicalization of newly learned words post-consolidation using a word-learning task. Bakker and colleagues (2015) taught participants novel words based on their native language and tested them during three different stages of lexicalization: before (untrained new words), right after training (recently learned new words), and 24 hours after training (new words trained one day before). Interestingly, decreased lower beta band power (16-21 Hz; time-window 300-500 ms) was induced for new words trained one day before when compared to untrained or recently learned new words. However, this consolidation effect was less clear or non-existent for upper beta (21-28 Hz; 500-700 ms) and alpha oscillatory bands, respectively. Indeed, recently learned new words showed a decrease in power in the upper beta band, similar to new words trained one day before, raising doubts about the exact role of beta oscillatory activity in the consolidation of newly learned words. As a caveat, Bakker et al.'s study required a motor response during the semantic even-related potential (ERP) decision task, possibly eliciting confounding preparatory beta motor effects (Alegre et al., 2004). Importantly for the present study, Bakker-Marshall et al. (2018) followed up on the previous electroencephalography (EEG) study using

magnetoencephalography (MEG) recording and failed to observe a decrease power in beta associated with new word consolidation. The authors noted the need to further investigate the intriguing role of beta power as an index of new word consolidation. More recently, Momsen and Abel (2022) used a contextual learning paradigm that allowed to build up the meaning of new words from context progressively (based on Mestres-Missé et al., 2007). They observed a decrease in alpha (8-12 Hz) and beta power (14-20 Hz) preceding the last presentation of the new word, which they interpreted as reflecting successful identification of the meaning of the new word. These findings are intriguingly in line with the abovementioned studies linking alpha and beta desynchronization prior to the pre-activation of contextually predictable words (León-Cabrera et al., 2022; Rommers et al., 2017; Wang et al., 2017; Terporten et al., 2019; Li et al., 2017), most probably associated with retrieving lexical and/or semantic features in highly constrained contexts (León-Cabrera et al., 2022; Gastaldon et al., 2020; Hustá et al., 2021; Klimesch et al., 2001; Momsen & Abel, 2022; Piai et al., 2015).

To gain a further understanding of the neurophysiological mechanisms of new word learning, we used a covert naming task that avoids motor confounds to examine how word lexicalization after learning affects neural oscillations. The original study for which the current dataset was collected tracked changes in lexical-semantic processing across five training sessions via N400 modulations (Ramos-Escobar et al., 2021). In the first experiment, learners exhibited a frontal N400 during the initial stages of learning, which gradually decreased in amplitude and shifted to parietal sites during later stages. A second experiment teased apart learning and repetition effects by separating participants into a learning group and a non-learning control group, replicating the initial findings only in the learning group. The change in N400 topography was interpreted as indicating that word learning requires both domain-general and language-specific mechanisms and involves distinguishable neural generators, depending on the learning stage. The current study delved into the oscillatory brain responses observed after consolidating new lexical items into memory.

We used a covert naming task that avoids motor confounds to examine how word lexicalization after learning affects neural oscillations. We performed analyses on the word-learning dataset collected on the first and fifth day of the study described above (Ramos-Escobar et al., 2021; see Fig. 1 for the task design). Word learning was measured pre- and post-training by covert naming (Figure 1), a form of internal word production that requires word-form retrieval from corresponding semantic representations (Dell & O'Seaghdha, 1992; Schmitt et al., 2000; Levelt, 1989; Rodriguez-Fornells et al., 2002; Piai & Zheng, 2019; Schriefers et al., 1990). Based on the previous literature cited above, we hypothesized that if novel word forms have been integrated into learners' lexicon on Day 5, this would be indexed by a decrease in alpha and beta power during covert naming as compared to Day 1 (pre-training) due to participants having fully or partially created associations between new object representations and potential new words.

1. Methods

1.1. Participants

A total of 25 healthy volunteers (13 females, mean age: 22 ± 3.19 years) participated in the study. The data of three participants was lost due to technical problems during the covert naming task. In addition, since we were interested in tracking learning-related changes, we only kept the trials of items that were successfully learned by the participant (i.e., correctly named in the last overt naming task of Day 5), excluding those that were already learned in Day 1 and thus not expected to undergo learning-related changes. Three participants were excluded because they had less than 35 correct trials available that fulfilled this criteria for analysis on Day 1 or Day 5. Therefore, 19 participants were included in the final data analyses (10 females, mean age = 21.8 ± 3.2 years).

Participants were all Spanish-Catalan bilinguals, except two Spanish monolinguals. They all had normal or corrected-to-normal vision, reported no history of neurological deficits, and were right-handed. Participants were briefed on the study procedure, provided written informed consent, and received a compensation of 60€ for their participation in the 5-day training sessions. The study received approval from the local ethics committee.

1.2. Procedure

The study consisted of five consecutive daily training sessions. On the first and last days, participants were first exposed to novel objects and new words during a pre-exposure task. Following this, they performed a learning task and an overt-naming task in the middle of learning. They then performed a covert-naming task, an overt-naming task, and a 2-alternative forced-choice (2-AFC) new word object matching task. On the second, third, and fourth days, participants engaged in the learning phase and the 2-AFC task. EEG data were recorded on Day 1 and Day 5 (**Figure 1**).

Before beginning the training sessions on the first day, participants completed a Language History Questionnaire (Bilingualism and Language Switching, Rodríguez-Fornells et al., 2012) and two tasks related to cognitive control and working memory: semantic and phonological fluency tasks (animal fluency and words starting with the letter 'p') and the WAIS-III Digit Span (mean score of forward and backward auditory span; see the original study for more details, Ramos-Escobar et al., 2021).

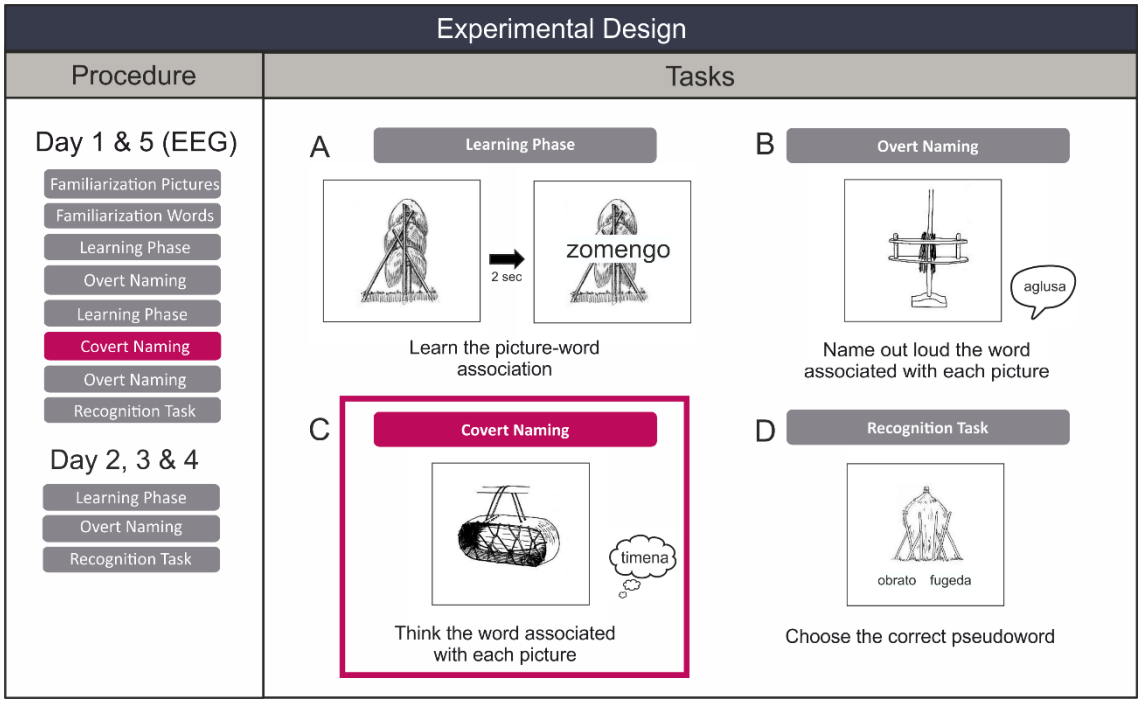

Figure 1. Adapted from the original study from Ramos-Escobar and colleagues (2021). Task design for the four different tasks used in the original study. Highlighted in blue is the Overt naming task, from which we used the results to select the items that participants correctly named in our Covert naming analysis. Highlighted and framed in red is the Covert Naming task we focused on in the current study.

1.3. Stimuli and Task

A set of 139 unfamiliar black-and-white images depicting farming-related artifacts was selected from the Ancient Farming Equipment (AFE) word-learning paradigm (Laine & Salmelin, 2010). Twenty students from the University of Barcelona who did not participate in the present study rated these

objects for familiarity (on a scale from 0, 'totally unfamiliar,' to 5, 'very familiar', mean rating: 2.58; SD: 0.61). Based on these ratings, the 120 least familiar objects were selected. A corresponding set of 120 tri-syllabic new words were created using the B-Pal software (Davis and Perea, 2005). These new words were phonotactically legal in Spanish and followed six different Consonant-Vowel (CV) structures (CVCVCV, VCVCVC, VCVCV, VCCVCV, CVCVCCV, and VCVCCV). They were presented visually.

Pre-exposure phase. Participants first completed a pre-exposure phase. In this stage, 120 novel objects were shown randomly for 2 seconds each. Additionally, five familiar objects from the AFE paradigm (those with the highest familiarity scores) were included. Participants were instructed to press a button when these target objects appeared to maintain a constant level of attention during this phase. This familiarization task (not reported here) was designed to examine brain responses to novel stimuli (both new words and images) when participants were instructed to observe rather than explicitly learn them. It was also intended to mitigate novelty-related ERP effects during the learning phase for the original study.

Leaning phase. The 120 object-new word pairs were presented randomly in a blocked design. Participants were instructed to pay attention to object-new word associations and learn as many as possible. During learning trials, participants saw a novel object on the screen for 2 seconds, and the associated new word was displayed above it for 1 second. The initial part of the learning phase comprised 480 trials divided into four blocks, followed by a second part (after the overt naming task) of 240 trials organized into two blocks. To minimize fatigue, a short break was provided after every 30 trials.

Overt-naming task. This task was used to assess learning, testing learners' ability to produce recently learned new words. Overt naming engages retrieval processes (Costa et al., 2009; Laine & Martin 2023), which facilitate learning when retrieval is suitably difficult (Agarwal et al., 2012; Pyc & Rawson, 2009; Roediger & Butler, 2011). 120 objects were displayed on the screen for 3 seconds, and participants were instructed to name the new word associated with the object overtly. Feedback was not provided between trials. Eight randomized sequences of the images were created, with their presentation counterbalanced across sessions and participants to control for order effects. Behavioural responses were digitally recorded. Objects named without syllable or phoneme errors were considered correct. No mispronunciations were made as the new words respected the phonotactic rules of Spanish. However, when participants failed to pronounce a syllable or phoneme, the overt naming was considered incorrect. Only the behavioural (and not the EEG) results of this task are included in the current study.

Covert-naming task. The current study focused on this task, which was introduced before the last overt naming task. It was designed to induce active retrieval processes while recording EEG activity without the muscular artifacts that can occur during overt naming (Strijkers et al., 2011). As mentioned above, inducing retrieval under demanding conditions is also believed to facilitate learning, which was our second aim. Participants saw the 120 objects on the screen for 3 seconds and were instructed to think about the new word without overtly naming it. A red square appeared around the object in 10% of the trials to maintain participants' attention during the task. During these trials, participants were asked to name that object overtly. To avoid list effects, five randomized lists were created (one list for each time the task was administered) and counterbalanced across sessions and participants.

1.4. Behavioral data analysis

All responses in the overt naming tasks were transcribed and categorized as either correct or incorrect. Responses were only considered correct if the participant uttered exactly the same name. We computed the percentage of correct responses in the last overt naming task of Day 1 and Day 5 for every participant and subjected them to a dependent-samples t-test to assess differences in performance before and after the learning protocol.

1.5. EEG data acquisition and analyses

The EEG signal was recorded with tin electrodes mounted in an electrocap (Electro-Cap International) arranged in 29 standard positions (FP1/2, F3/4, C3/4, P3/4, F7/8, T3/4, T5/6, Fz, Cz, Pz, FC1/2, FC5/6, CP1/2, CP5/6, PO1/2, Oz) and using a BrainAmp amplifier (BrainVision acquisition software, Brain Products) with a sampling rate of 250 Hz. All electrode impedances were checked and kept below 5 kΩ during the recording session. The input signal was filtered with a high-pass filter at 0.01 Hz and a notch filter at 50 Hz to attenuate power line noise. The electrode in the FCz position served as the ground, an external electrode placed at the lateral outer canthus of the right eye was used as the online reference, and an electrode located in the infraorbital ridge of the right eye served to monitor vertical eye movements.

We analyzed the electrophysiological data recorded during the covert naming task on Day 1 and Day 5. The data were analyzed using the Fieldtrip toolbox version 20230108 (Oostenveld et al., 2011) running under MATLAB version 9.11 (R2021B). EEG data were re-referenced off-line to mean activity at the two mastoidal electrodes. For each participant and covert naming session (Day 1 and Day 5), the continuous EEG data were segmented into epochs of 3.1 s, encompassing 1.1 s before and 2 s after picture onset. The 10% of trials in the task where the participant had to name the object overtly were excluded from further analysis. Then, we performed artifact detection and rejection. First, we excluded epochs with voltage amplitudes ±100 microvolts in any electrode within the -0.1 to 1 s interval (time-locked picture onset). Additionally, any remaining epochs with artifacts (eye blinks, eye movements, electrode drifting, or muscle activity) were rejected through visual inspection. After artifact rejection, there were no statistically significant differences between the average number of trials on Day 1 (mean = 87.1 trials, std = 10.4 trials) and Day 5 (mean = 87.8 trials, std = 12.8 trials) [$t(1,21) = -.263$, $p = .795$].

As a result, and after applying the exclusion criteria (see the section on Participants above), the final sample (N = 19) had an average of 57 valid trials available per participant and session, i.e., Day 1 or Day 5 (std = 13.9 trials; min = 35 trials, max = 91 trials). There were no statistical differences in the number of available trials on Day 1 (mean = 56.7 trials; std = 13.4 trials) and Day 5 (mean = 57.3 trials; std = 14.7 trials) [$t(1,18) = -.308$, $p = .761$].

1.6. Time-frequency analyses

For every participant and session (Day 1 and Day 5), we computed the time-locked event-related potential and subtracted it from every trial-level time-locked data to keep only induced activity (Kalcher & Pfurtscheller, 1995; Rommers & Federmeier, 2017). Time-resolved power was computed by applying a Hanning taper with fixed length of 300 ms (from 1 to 40 Hz in steps of 20 ms in the -1.1 to 2 s time-window, time-locked to the onset of the picture). This taper provided a spectral resolution of 3 Hz and temporal resolution of 300 ms, which was considered a good time-frequency trade-off considering the targeted frequency range (alpha/beta; alpha from 8-12 Hz and beta from 13-25 Hz approximately) and the probable duration of the underlying high-level cognitive processes that were at focus (at or above 300 ms).

For statistical analyses, the grand-averaged time-frequency data was baseline corrected to the 100 ms pre-stimulus period, and a cluster-based permutation analysis was applied on the -0.1 to 1-second interval time-locked to picture onset. All time points and electrodes were blindly scanned for adjacent frequencies, time points, and electrodes with a similar difference across conditions. Every sample (frequency x time x channel) was compared between the two sessions (Day 1 and Day 5) using a paired-sample-statistic. Then, adjacent time-frequency-channel samples were clustered based on a *t*-value threshold of ± 2.10 for an alpha level of 0.05 with 18 degrees of freedom. The permutation *p*-value was computed using the Monte Carlo method involving 5000 random permutations. Only effects with a permutation *p*-value below 5% (two-tailed testing) were considered significant.

2. Results

2.1. Behavioral results

For the overt naming task, we computed the percentage of correct responses for Day 1 and Day 5 and compared their means with a dependent samples t-test. There was a clear learning effect with participants increasing their number of correct responses between Day 1 (mean = 13.6%; std = 11.3) and Day 5 (mean = 76.9%; std = 18.9; $t(1,18) = -18.6$, $p < .001$, see **Figure 2**).

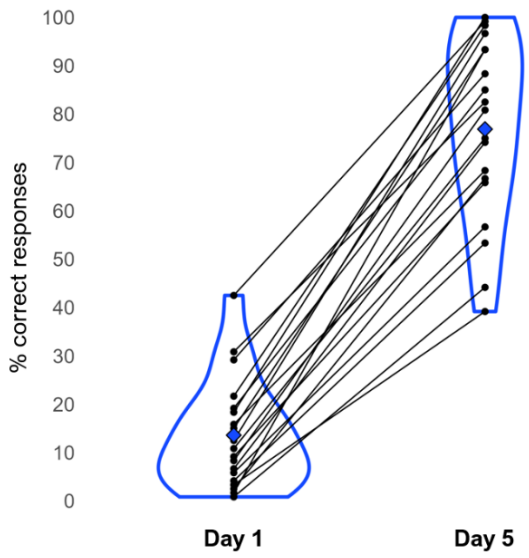

Figure 2. Violin plots of the performance (percentage of correct responses, y-axis) in the overt naming task on Day 1 and Day 5 (x-axis). The black dots represent individual participants and the lines connect data points from the same participant in each session. The blue diamond-shaped symbol indicates the group mean performance.

Time-frequency results

Figure 3 shows the grand-averaged time-frequency maps of the covert naming task in each session (Day 1 and Day 5). As can be seen, picture presentation induced a long-lasting power decrease (strong desynchronization) of alpha (8-12 Hz) and lower beta (18-25 Hz) power after 150-200 ms on both days. This effect was predominant over posterior and occipital electrodes. In addition, there was a broadly distributed power increase in the theta band (4-8 Hz) approximately from 50-150 ms after picture presentation on both days.

Critically, the power decrease in the alpha and beta bands was more pronounced on Day 5 than on Day 1, suggesting that desynchronization in these frequency bands may reflect learning-related processes associated with the retrieval of the learnt new words. Accordingly, results of the cluster-based permutation test revealed one statistically significant negative cluster ($p < .001$), indicating a more pronounced power decrease on Day 5 compared to Day 1 (**Figure 4A**). The cluster mainly encompassed the alpha and lower beta bands and was most prominent at posterior and occipital sites within an interval ranging from about 150 ms to 1 second after picture presentation, although it also encompassed central and frontal electrodes (**Figure 4B**). Importantly, for each participant, we only kept the trials of words that were not learnt by Day 1 but that were eventually learnt in Day 5 (the learning status was evaluated through the performance in an overt naming task, see **Figure 2**). Therefore, it is likely that any difference between sessions reflects learning-related activity. In turn, the power changes in the theta band were not statistically significant between sessions.

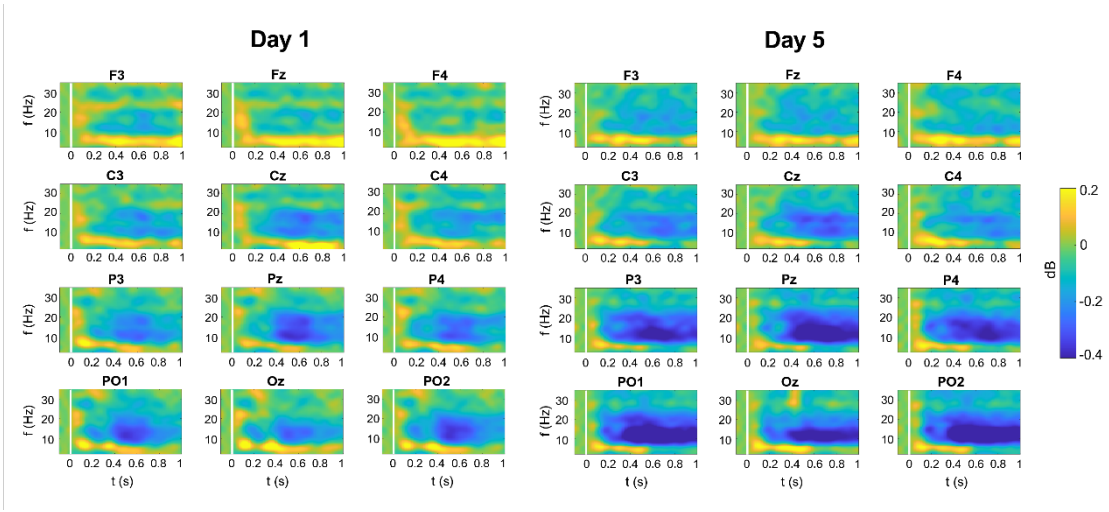

Figure 3. Grand-averaged time-frequency plots showing the oscillatory activity in the covert naming task of Day 1 and Day 5 (in dB) relative to baseline (-0.1 to 0 s time-locked to picture presentation) for frontal (F3, Fz, F4), central (C3, Cz, C4), posterior (P3, Pz, P4), and posterior-occipital (PO1, Oz, PO2) electrode positions. All plots encompass the frequency range from 0 to 35 Hz (y-axis) and the temporal interval from -0.1 to 1 second (x-axis) time-locked to picture onset. Picture onset is indicated by white vertical lines at 0 s.

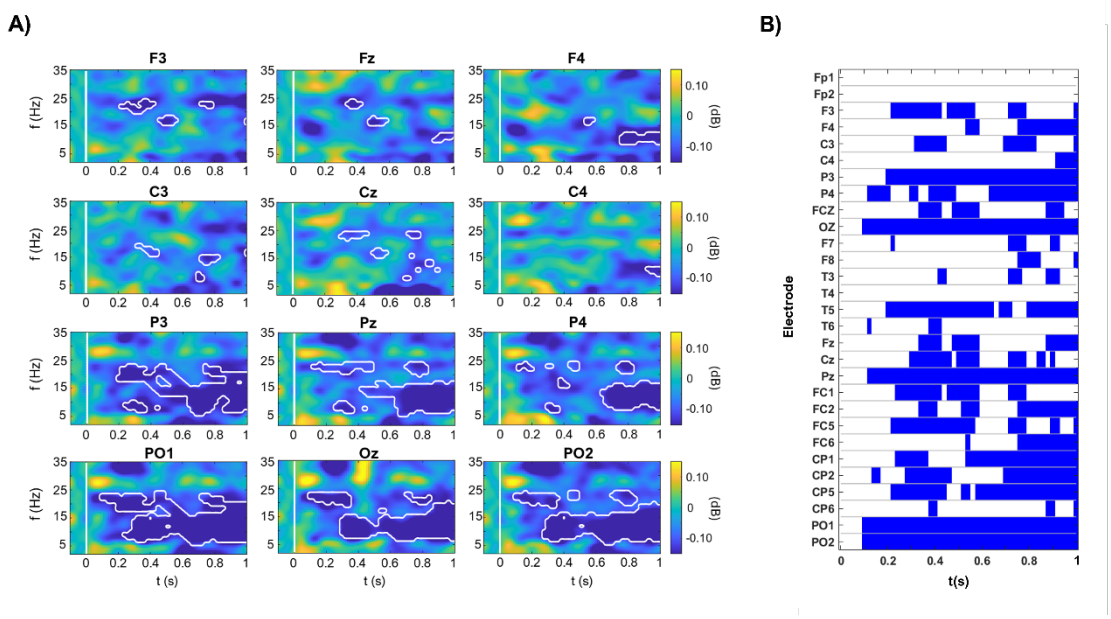

Figure 4. A) Grand-averaged time-frequency plots showing learning-related power changes (Day 5 minus Day 1) (in dB) relative to baseline (-0.1 to 0 ms time-locked to picture presentation). The statistically significant cluster is outlined in white. **B)** Raster plot of the time course of the significant cluster in the 8-25 Hz frequency range across all electrodes in the interval from 0 to 1 second after picture presentation.

The finding of a single significant cluster supports an interpretation of concurrent alpha-beta desynchronization as a unitary phenomenon in this study. However, these two frequency bands have also been associated with independent cognitive processes. Of special interest is the implication of the beta band in motor-related processing, which is often a confound in production studies that seek to disassociate motor-related activity from semantic and lexical processing. Thus, to gain a deeper understanding of the cognitive processes involved in this task, we also inspected the spatial and temporal dynamics of these two frequency bands separately. **Figure 5** shows the evolution of the topographical distribution of mean power changes (Day 5 minus Day 1) at picture onset for the alpha and beta range individually. From 200 ms after picture onset, both frequency bands exhibited relatively enduring power decreases at parieto-occipital electrodes with a similar time-course (**Figure 6**). In addition, in the alpha band (8-12 Hz), right frontal electrodes exhibited a power decrease approximately from 400 to 1000 ms after picture onset. In turn, in the beta band (18-25 Hz), power desynchronized at left frontal sites from 200 ms to 1000 ms. Therefore, each frequency band might have contributed distinctly to the frontal effects captured by the cluster.

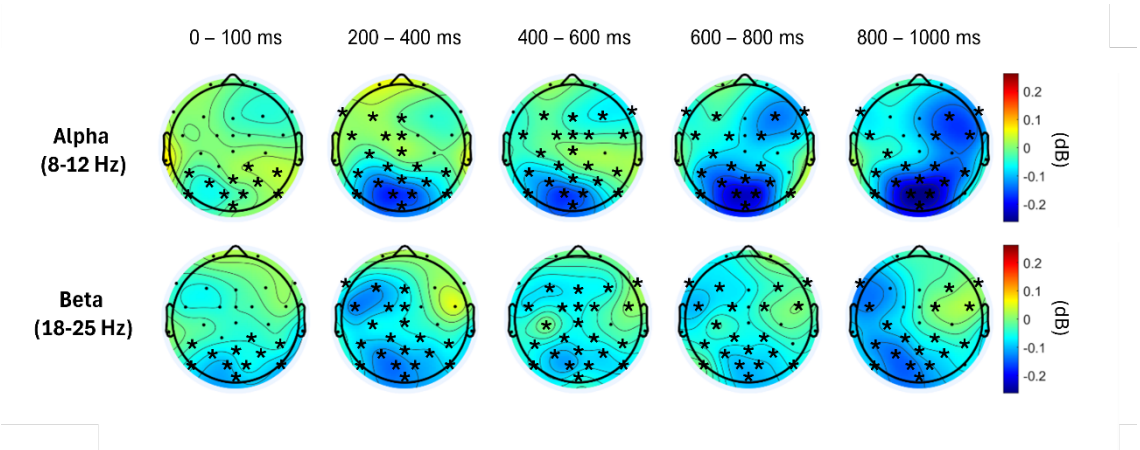

Figure 5. Topographical maps of the mean power changes (Day 5 minus Day 1; in dB) for the alpha (8-12 Hz) (top) and beta range (18-25 Hz) (bottom) in the 0 to 1 second interval time-locked to picture onset, in steps of 100 ms. In every time interval, asterisks mark the electrodes that were part of the s significant cluster which encompassed both frequency bands.

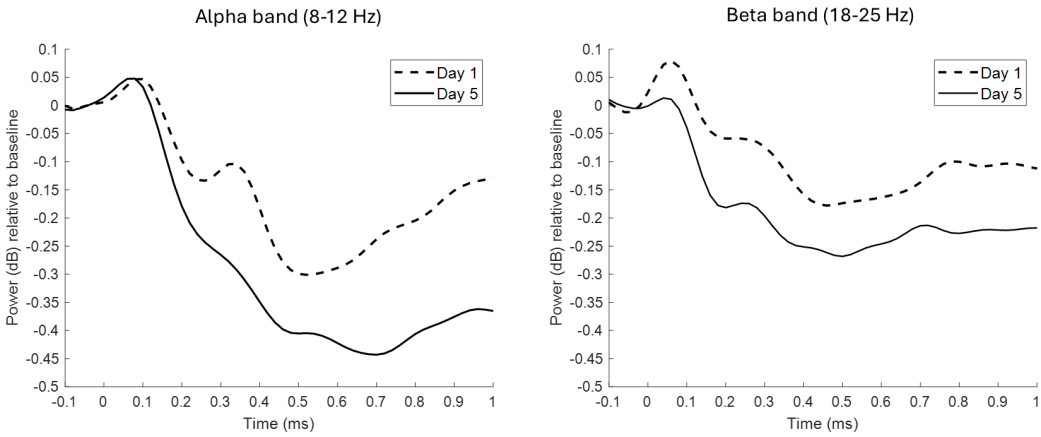

Figure 6. Time course of learning-related power changes in the alpha (8-12 Hz) (right) and lower beta (18-25 Hz) (left) bands for Day 1 (discontinuous lines) and Day 5 (continuous lines) at posterior-occipital electrodes (average of activity at Pz, P3, P4, PO1, PO2 and Oz electrodes).

Discussion

The current study explored the oscillatory activity in alpha and beta bands when participants retrieved newly learned words after consolidation. Previous studies provided conflicting results regarding the role of these frequency bands in new word learning (Bakker et al., 2005; Bakker-Marshal et al., 2018; Momsen et al., 2022). Here, participants were taught to associate new words with unknown objects and asked to overtly and covertly name visually presented items during the first and last day of a five-day training experiment. We analysed oscillatory brain activity related to retrieving new words focusing on alpha (8-12 Hz) and beta (13-25 Hz) band desynchronization while participants saw images and covertly retrieved new words, pre and post consolidation. We compared cortical oscillatory activity during covert naming at the first and fifth learning sessions, observing a robust concurrent alpha (8-12 Hz) and lower beta (18-25 Hz) power decrease 200-1000 ms post picture presentation. For both the alpha and beta frequency ranges, the effect was distributed over the parieto-occipital sites. When inspecting each frequency band separately, the power decrease in the alpha band encompassed left frontal electrodes from 400 to 1000 ms and the lower beta band (18-25 Hz) showed decreases in left frontal sites from 200 ms to 1000 ms.

One important limitation in previous studies examining cortical oscillations during retrieval of newly learned words is the confounding role of motor responses (Bakker et al., 2015). Alpha-beta desynchronization, while often linked to semantic processing, can also reflect visual processes (Hanslmayr et al., 2011) and cortical-subcortical motor activity (Neuper et al., 2006; Pfurtscheller & Lopes da Silva, 1999). Notably, in tasks requiring language articulation, alpha-beta desynchronization has been localized in the motor and premotor cortex and the left inferior frontal gyrus pre-speech, associated with verbal motor planning, even in the absence of semantic processing (Herman et al., 2013; Jenson et al., 2014). By using a task requiring covert articulation, we minimized motor confounds, thereby circumventing alpha and beta oscillations that index action preparation and execution (Alegre et al., 2004; Pfurtscheller & Lopes da Silva, 1999). Given that our task did not require a motor response, changes in beta and alpha desynchronization most likely reflect the retrieval of newly built lexical-semantic associations, rather than motor activation or preparatory activity (Hanslmayr et al., 2009). However, even covert naming raises the possibility of covert articulation. A substantial body of literature has addressed the challenge of disentangling motor-related and language-related alpha-beta desynchronization. These studies emphasize the importance of task design and localization of desynchronization patterns to dissociate linguistic and motor processes. This framework allows us to interpret our findings within the broader context of how alpha-beta oscillations support language processing.

To distinguish motor from language-related contributions of beta desynchronization, Scaltritti et al. (2020) compared silent reading and copy-typing tasks using emotionally valenced words. While motor-related beta desynchronization was specific to typing, both tasks elicited an earlier beta desynchronization linked to language processing. Similarly, Piai et al. (2020) used MEG to differentiate lexical-semantic retrieval from motor processes in tasks involving picture naming and conceptual judgment. For picture naming, beta desynchronization was localized to left temporal and ventral premotor areas, implicating lexical retrieval and verbal motor planning. By contrast, the judgment task elicited beta desynchronization in left posterior temporal and inferior parietal areas, alongside right motor cortex activation, associated with conceptual processing and manual response preparation. Another MEG study by Gastaldon et al. (2020) examined alpha-beta desynchronization during language comprehension and production in high- and low-constraint contexts. In comprehension tasks, highly constraining sentences elicited alpha-beta desynchronization in left lateralized language production areas, suggesting overlap between comprehension and production mechanisms. This activity also appeared over right posterior temporo-parietal regions, linked to

internal modeling and contextual updating. Across these tasks, alpha-beta desynchronization indexed rich linguistic information encoding and retrieval, with its spatial distribution varying by task demands—whether lexical retrieval, language production, or motor preparation. Our findings show alpha and beta desynchronization in right frontal, left frontal and mainly parieto-occipital areas, as opposed to motor-related areas (i.e., ventral premotor areas as in Piai et al. 2020), reinforcing the interpretation that this activity reflects language-related rather than motor articulatory processes. This highlights the utility of alpha-beta desynchronization as a marker of language processing, distinct from motor contributions, and advances our understanding of the neurophysiological correlates of lexical-semantic retrieval.

A growing body of literature relates alpha and beta power decreases with the encoding and retrieval of semantic representations. Previous studies have shown that the magnitude of alpha and beta desynchronization correlates with the amount of information retrieved from memory (Khader & Rösler, 2011) and with greater semantic encoding and elaboration (Hanslmayr et al., 2009; Klimesch et al., 1999), which has brought about a comprehensive interpretation of alpha-beta desynchronization reflecting the richness of the information represented in the system during semantic encoding and retrieval (Hanslmayr, Staudilg & Fellner, 2012; Griffiths et al., 2019). In agreement with this proposal, alpha and beta desynchronization precedes the utterance of contextually predictable words, possibly indexing lexical-semantic retrieval during language production (Gastaldon et al., 2020; Piai et al., 2014, 2015; Piai & Zheng). Also, recent studies in language comprehension have linked alpha and beta power decreases to the prediction (or, put differently, the anticipated retrieval) of the lexical-semantic features of final words in strongly constraining sentences, compared to weakly constraining ones (in both written and spoken comprehension, León-Cabrera et al., 2022; Li et al., 2017; Rommers et al., 2017; Terporten et al., 2019; Wang, Hagoort et al., 2018). Our results align particularly well with some of these comprehension studies reporting alpha and beta power decreases over left frontal (Gastaldon et al., 2020; Wang et al., 2017; Rommers et al., 2017; León-Cabrera et al., 2022) and parieto-occipital electrodes (Rommers et al., 2017; León-Cabrera et al., 2022). Similarly, the alpha-beta desynchronization observed in this study might reflect lexical-semantic retrieval of newly learnt words that have been integrated into semantic memory after consolidation. This interpretation could also account for recent findings in other word learning studies linking alpha and/or beta to word learning (Bakker et al., 2015; Momsel & Abel, 2022; but see Bakker-Marshal et al., 2018 for discrepant results). Although not directly related to word-learning, alpha power decreases have also been observed in a lexical decision task for real words versus ambiguous new words and for ambiguous new words versus full new words (Strauß et al., 2014).

Most previous studies investigating the neural correlates of newly learned novel words through time-frequency and ERPs (Bakker et al., 2015; Batterink & Neville, 2011; Hawkins & Rastle, 2016; Havas et al., 2017; Kaczer et al., 2018; Liu & van Hell, 2020; Tamminen & Gaskell, 2013; Liu & van Hell, 2020) have relied on lexical competition or semantic priming to measure word acquisition. However, semantic priming does not necessarily indicate full lexicalization (see Korochkina et al. 2024 for a detailed discussion). In contrast, our study required participants to produce learned words overtly, and only those that could be explicitly recalled were included in the time-frequency analysis of covert naming. We believe this approach offers a more robust measure of novel word lexicalization, allowing for a clearer interpretation of the processes reflected in our time-frequency results. Similarly, a recent study used an incidental learning task, in which new words are learned through a dialogue-like situation, in which the final production of the new word was used as a potential measure of fast lexicalization (Lemhöfer et al., 2025).

Furthermore, a key distinction between our study and previous oscillatory ones (Bakker et al., 2015; Momsen & Able, 2022) is our use of explicit word-to-referent associations to link new words to *unknown* objects – a task considered more demanding than associating novel words with familiar items or definitions (see Laine & Salmelin, 2010). In relation to this paradigm, it has recently been shown that learners tend to automatically assign meaning to unfamiliar referents quite rapidly after initial exposure (Laine et al., submitted). Nonetheless, overnight consolidation likely plays an important role in processing information involving completely novel objects, as they cannot be readily associated with pre-existing familiar object representations. Consolidation is crucial for lexicalization in that it stabilizes semantic representations (Gilboa & Moscovitch, 2021), rendering them more available for retrieval during comprehension and production. According to the complementary learning systems (CLS) theory, word learning begins with quick familiarization, followed by a slower neocortical lexical consolidation that entails shifting from hippocampal to neocortical memory systems via a dynamic interaction between the two during sleep (Davis & Gaskell, 2009; Gore et al., 2022; Singh et al., 2022). Indeed, in a previous study (Havas et al., 2018) the pairing of new words to unfamiliar objects showed less beneficial sleep consolidation effects than when new words were associated with familiar objects. Thus, the capacity to use existing knowledge schemas to encode new representations might enhance the potential consolidation of the new traces. In the present study, new associative links are needed to be stablished between the new lexical candidate and the new unfamiliar object, as well as potential associations between this new object with already existing semantic information and other words in lexical-semantical networks (e.g., "*this new object resembles a tool I know*") (Laine et al., submitted). It is reasonable to conclude that during word learning, learners access and retrieve newly formed and progressively consolidated lexical-semantic representations that facilitate optimal information processing. Therefore, in our study, alpha-beta desynchronization during the retrieval of newly learned words reflects successful consolidation of these new words.

To conclude, our study highlights how newly learned lexical items become integrated progressively into existing lexical-semantic networks through learning. We hypothesize that our findings showing a pattern of alpha-beta desynchronization during retrieval reflects successful consolidation of new lexical-semantic representations. This evidence aligns with previous research linking alpha and beta activity to lexical-semantic retrieval in different tasks. This change in oscillatory patterns appears to act as a marker of successful learning. Finally, our study paves the way for future investigation into the neural correlates of word retrieval across different phases of language learning. Although we focused on new word retrieval during the first and fifth day of training, future studies could benefit from measuring retrieval over several days and weeks post-training, to better elucidate the time course of lexicalization.

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Authors contribution
NRE, CF, ML, and ARF planned the study. NRE performed the EEG measurements. PLC analyzed the data and performed the statistical analyses. AZ, PLC, CF, ML, and ARF contributed to the interpretation of the data and wrote the manuscript

Data and code availability statement

The anonymized data and Matlab scripts necessary to reproduce the analyses presented here are available on the OSF platform (https://osf.io/jzwb2). The materials necessary to attempt to replicate the findings presented here are not publicly accessible but are available from the corresponding author upon request.

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