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**Attentional Refreshing in Working Memory and its Interplay with Long-Term Memory:  
A Behavioral and EEG Study**

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## Abstract

Despite the growing interest in the study of attentional refreshing, the functioning of this working memory maintenance mechanism, including its cerebral underpinnings, is still debated. In particular, it remains unclear whether refreshing promotes long-term memory, and whether it in return depends on long-term memory content to operate. Here, we used direct maintenance instructions and measured brain activity to investigate working memory maintenance with two objectives: (1) test if different behavioral and oscillatory patterns could be observed when participants were instructed to use attentional refreshing vs. verbal rehearsal, and (2) observe whether and how refreshing is modulated when maintaining novel (pseudowords) vs. familiar (words) memoranda. We conducted an EEG experiment using a modified Brown-Peterson task, in which we manipulated the type of maintenance engaged through explicit instructions (verbal rehearsal vs. refreshing), the type of memoranda (words vs. pseudowords), and the memory load (2 vs. 6). Using scalp EEG, we measured both neural oscillations during working memory maintenance and ERPs during the concurrent parity judgment task. For words, we showed that verbal rehearsal benefited more short-term recall while refreshing benefited more delayed recall. In keeping with these behavioral differences between maintenance instructions, frontal-midline theta power increased with memory load only when using verbal rehearsal, while occipito-parietal alpha desynchronization was larger with refreshing than verbal rehearsal. When maintaining pseudowords, verbal rehearsal also benefitted short-term recall more than refreshing. However, no long-term memory benefit of refreshing was observed for pseudowords, and oscillatory activity was not different under the two maintenance instructions. Our results provide new evidence supporting the independence between attentional refreshing and verbal rehearsal, and bring new insight into refreshing functioning. We discuss the possible interpretations of these results and the implications for the attentional refreshing literature.

*Keywords:* working memory, long-term memory, verbal rehearsal, refreshing, EEG, alpha rhythm, theta rhythm

## Introduction

Working memory (WM) is defined as a capacity-limited system responsible for the short-term maintenance and manipulation of information (Baddeley & Hitch, 1974). Two maintenance mechanisms are mainly considered in the case of verbal information: verbal rehearsal and attentional refreshing (Camos et al., 2009). Verbal rehearsal (also called *articulatory rehearsal* or *subvocal repetition*) is a silent verbal repetition of information, efficient at short-term with low attentional demand (Atkinson & Shiffrin, 1968; Baddeley et al., 1975; Belleville et al., 1992; Naveh-Benjamin & Jonides, 1984). On the other hand, attentional refreshing is defined as a domain-general maintenance mechanism that operates through a brief attentional focus to increase the activation level of information recently presented, encoded, or retrieved (Camos et al., 2018). Attentional refreshing is hypothesized to be independent of verbal rehearsal because they are differently affected by task constraints, have a different impact on recall performance, and have distinct brain networks subtending them (Camos, 2015; Camos et al., 2018; Camos & Barrouillet, 2014; Mora & Camos, 2013). However, the functioning of refreshing and its interplay with long-term memory (LTM) are still unclear (Camos et al., 2018).

### **Attentional refreshing functioning**

#### ***Manipulations of refreshing***

Since refreshing relies on attentional resources, its availability during maintenance can be manipulated by varying the concurrent attentional demand. To this end, the concept of cognitive load has been developed in the *Time-Based Resource-Sharing* (TBRS) model as the portion of the total time of the task during which attention is diverted from maintenance (Barrouillet et al., 2004). The cognitive load can be manipulated through various methods, such as varying the pace of a concurrent processing task or its difficulty. Increasing cognitive load has been shown to impair WM maintenance (e.g., Barrouillet et al., 2007, 2011), which

is interpreted by some authors as an argument in favor of the existence of refreshing and its contribution to WM maintenance. Other studies have supported the refreshing hypothesis using direct maintenance instructions to use attentional refreshing, either in response to a cue (M. R. Johnson et al., 2007; Raye et al., 2007; Souza et al., 2015, 2018) or as a general instruction for all trials (Camos et al., 2011). This way, it has been shown that short-term recall performance increased with the number of cue-induced refreshing (Souza et al., 2015, 2018) and that the phonological similarity effect disappeared under refreshing instructions, while it was observed when participants were instructed to use verbal rehearsal (Camos et al., 2011).

However, attentional refreshing is still poorly understood, leading to multiple debates in the literature around its functioning. For instance, the question of whether cognitive load manipulations really reflect refreshing is still debated as the benefit of free time during a WM task might be attributed to other mechanisms such as short-term consolidation (Souza & Oberauer, 2017), elaboration (Loaiza & Lavilla, 2021), or a WM encoding resource that is replenished over time (Mızrak & Oberauer, 2021; Oberauer, 2022). It has also been proposed that free time after attentional displacement (e.g., in a complex span task) is used for covert retrievals, a repetitive retrieval practice from LTM that facilitates later recall from LTM (e.g., Loaiza et al., 2020; Loaiza & McCabe, 2012; McCabe, 2008), consistent with the view that LTM is involved in WM recalls (Rose et al., 2014, 2015). Moreover, the effect of cognitive load manipulations on short-term recall is in some cases not replicated (Ricker & Vergauwe, 2020, 2022). Thus, the study of refreshing could benefit from additional data obtained using alternative manipulations and more direct measurements.

Some studies also raised the question of whether refreshing interacts with LTM, both in terms of whether refreshing promotes long-term recall, but also whether refreshing relies on the content of LTM to function. Furthermore, showing that verbal rehearsal and refreshing

impact differently short-term and long-term recall would provide additional evidence of the distinction between these two maintenance mechanisms. These questions will be detailed in the following sections.

### ***Effect of refreshing on long-term memory***

Over the years, researchers have become increasingly interested in how WM can promote long-term retention of maintained information, especially through maintenance mechanisms. It has been shown that adding a concurrent processing task in-between memoranda (i.e., complex span tasks vs. simple span tasks) impairs short-term recall but improves delayed recall (Loaiza & McCabe, 2012; McCabe, 2008). The interpretation of this result was that memoranda are covertly retrieved after each processing item, possibly through refreshing, which increases the context-content binding and facilitates their later recall. Consistently, it has been found that manipulating cognitive load not only affects short-term recall, as described above, but also long-term recall performance (Camos & Portrat, 2015; Jarjat et al., 2018, 2020). These results led the authors to suggest that attentional refreshing also contributes to LTM (Camos & Portrat, 2015; Jarjat et al., 2018, 2020), in contrast to verbal rehearsal which only affects short-term recall (Camos & Portrat, 2015). This proposition is still debated however, as other studies have sometimes failed to replicate the cognitive load effect on delayed recall (Labaronne, Jarjat, et al., 2023; Loaiza et al., 2023) or argued that the delayed recall improvement is due to other mechanisms such as elaboration (Bartsch et al., 2018).

### ***Refreshing in the absence of prior LTM content***

As most studies investigating refreshing are conducted using known material (e.g., words or letters), it is still unclear if refreshing can operate on items involving content not already in LTM. A study investigated the long-term benefit of WM when maintaining a novel material, pseudowords. The authors found that the benefit of complex over simple span on

delayed recollection is observed with words, but not pseudowords (Loaiza et al., 2015). Coherently, it has been reported that a concurrent processing task has an increasingly detrimental effect over longer retention intervals for letters of the Latin alphabet, that were familiar to the English-speaking participants, but not for characters unfamiliar to the participant (e.g., Greek, Cyrillic, or Arabic characters; Ricker & Cowan, 2010). Similarly, the maintenance of unfamiliar melodies is disrupted by concurrent articulatory suppression, but not concurrent attentional demand (Nees et al., 2017). Furthermore, refreshing postpones concurrent attentional processing, except when maintaining character fonts, suggesting that fonts cannot be refreshed (Vergauwe et al., 2014). Together, these results suggest that refreshing cannot operate on novel or unfamiliar material, for which there is no representation in LTM, and thus that refreshing may rely on semantic representations or retrieval from LTM. However, recent studies did not support this proposal as items' lexicality and frequency modulate neither the effect of cognitive load (Camos et al., 2019; Labaronne, Jarjat, et al., 2023) nor refreshing speed (Camos et al., 2019). Similarly, cognitive load does not interact with semantic relatedness between words (Rosselet-Jordan et al., 2022) or with the recall benefit of semantic cues over phonological cues (Loaiza & Camos, 2018). These recent results suggest that refreshing does not operate by accessing the LTM content. Thus, while the question of whether refreshing relies on LTM has important implications for understanding its functioning, the literature presents conflicting results.

Given the aforementioned issues, employing neuroimaging techniques as a more direct means of measuring refreshing, combined with explicit instructions regarding the maintenance mechanism to use, could provide novel insights into refreshing functioning and its interplay with LTM.



## Neural correlates of working memory maintenance

### *Refreshing-related activations*

There is substantial literature investigating WM using fMRI, EEG, and MEG, that commonly links it to activity in frontal and posterior regions. fMRI studies suggest that refreshing activates the left dorsolateral prefrontal cortex, anterior prefrontal cortex, and parietal regions (Fanuel et al., 2021; M. K. Johnson et al., 2005; M. R. Johnson et al., 2007; Raye et al., 2002, 2007). Critically, activation of the left dorsolateral prefrontal area was specific to refreshing and is thought to be associated with foregrounding a specific mental representation, while verbal rehearsal selectively activated the ventrolateral prefrontal cortex (Raye et al., 2007).

Additionally, fMRI results suggest that refreshing modulates activity in perceptual regions (i.e., parahippocampal place area for scenes, fusiform face area for faces) specific to the refreshed stimulus (M. R. Johnson et al., 2007; Johnson & Johnson, 2009). Other studies, while not specifically mentioning attentional refreshing, have also observed item-dependent activations during WM maintenance. EEG studies on visual WM identified a contralateral delayed activity (CDA; also referred to as *sustained posterior contralateral negativity* or *contralateral negative slow wave*) in posterior areas during maintenance of visual memoranda that correlates with memory load (Adam et al., 2018; Jolicœur et al., 2008; Villena-González et al., 2020; Vogel & Machizawa, 2004). In the same line, the use of multivariate pattern analyses revealed that categorical information on the item type exists in the EEG signal during WM maintenance (M. R. Johnson et al., 2015; LaRocque et al., 2013), supporting the existence of distinct activations depending on the memoranda.

Refreshing-related activity in prefrontal and item-specific regions led authors to suggest a two-phase model in which early frontal control initiates the following reactivation of posterior representational areas (M. R. Johnson et al., 2007, 2015). Supporting this

proposition, EEG examination of the time course of refreshing indicated an earlier (400 ms) right frontal and bilateral parietal, temporal, and occipital positive peak, and a latter (800-1400 ms) posterior sustained positivity (M. R. Johnson et al., 2015).

### ***Neural oscillations during working memory maintenance***

These previous studies rely on a directed-refreshing paradigm in which, following earlier behavioral studies (e.g., M. K. Johnson et al., 2002), participants were cued to refresh a single item for an extended duration (e.g., 1500 ms in M. R. Johnson et al., 2007). However, increasingly, behavioral research has focused on refreshing of multiple items during maintenance period, based on the idea that refreshing is a fast process (e.g., 50 ms per item in Vergauwe et al., 2014; see also Lemaire et al., 2018) happening spontaneously and repeatedly during free time in the task (Barrouillet et al., 2004, 2007; Barrouillet & Camos, 2012). It thus seems relevant to try to capture this continuity in the mechanism. For this purpose, studying brain oscillations seems adequate as they are less time-locked than ERPs and allow the capture of faster alternation between maintenance and processing than fMRI. A large literature exists on oscillatory activity during WM maintenance and revealed a particular involvement of frontal theta and occipito-parietal alpha oscillations (for a review, see Pavlov & Kotchoubey, 2022).

The involvement of frontal theta oscillations in WM is strongly supported, with many reports of a theta increase with memory load during a WM task (e.g., de la Chapelle et al., 2023; Gevins et al., 1997; Jensen & Tesche, 2002; Meltzer et al., 2008; Onton et al., 2005; Scheeringa et al., 2009). One hypothesis is that theta plays a role in the maintenance of the temporal relationship between memoranda (Hsieh et al., 2011; Roberts et al., 2013). For instance, in the study conducted by Hsieh and colleagues (2011), participants were required to maintain either information about items or their temporal order. Results showed that frontal-midline theta power was increased when maintaining order compared to items. Expanding on

this idea, the *theta-gamma neural code theory* (Lisman & Idiart, 1995; Lisman & Jensen, 2013) proposes that a sequence of items is maintained through successive gamma cycles, nested in theta oscillations that serves as a temporal delimitation of the multi-item sequence.

WM maintenance is also frequently associated with changes in posterior alpha activity. While most studies reported an increase in alpha power with higher memory load (e.g., Jensen et al., 2002; Proskovec et al., 2019; Tuladhar et al., 2007), some reported a decrease with memory load (e.g., Meltzer et al., 2008; van Ede et al., 2017). Thus, there is a discrepancy in the direction of the effects, with about 20% of verbal WM studies reporting a decrease and 80% an increase during maintenance, and proportions close to 40% and 60% respectively for visual WM studies (Pavlov & Kotchoubey, 2022). The cause of this disparity is unclear. Multiple authors have made the hypothesis that alpha has a role in inhibitory processes (Bonfond & Jensen, 2012; Händel et al., 2011; Jensen & Mazaheri, 2010; Jokisch & Jensen, 2007), while gamma increase reflects activity in a region (Jensen & Mazaheri, 2010; Jokisch & Jensen, 2007). Thus, it is posited that the recruitment of a perceptual area induces a decrease in alpha power coupled with an increase in gamma power in this region. This view is supported by the observation that the right posterior alpha power increase was negatively correlated with the BOLD signal in the right primary visual cortex during WM maintenance (Scheeringa et al., 2009). Thus, van Ede (2018) argued in a review that the difference in alpha directionality can be explained by differences in the relevance of sensory areas, with visual WM recruiting visual areas and thus leading to a decrease in alpha power in visual areas sites, while verbal WM leads to an alpha increase in those sites as an interference protection. However, Pavlov and Kotchoubey (2022) tested in a meta-analysis two hypotheses to try to explain the directionality of alpha power modulation, but found neither the modality (visual vs. verbal) nor the type of presentation (simultaneous vs. successive) to be satisfying.

On top of their involvement in WM maintenance, both theta and alpha oscillations have been linked to WM's promotion of LTM encoding. Khader and colleagues (2010) used a matching-to-sample task followed by a surprise LTM recognition test. They found that occipital-to-parietal alpha and midfrontal theta power during WM maintenance were increased for later-remembered compared to later-forgotten stimuli. These results are in line with the view that WM maintenance contributes to LTM formation. Moreover, it appears that the WM-LTM link is reflected in the alpha and theta activity during WM maintenance, making these frequency bands potentially very interesting to investigate the interplay between the two memory systems. However, to our knowledge, studies measuring neural oscillations investigated WM maintenance in a general manner, without differentiating maintenance mechanisms. Thus, the specific oscillatory pattern of refreshing has not yet been described.

### **Present study**

In the present study, we aimed to better understand attentional refreshing functioning and its interplay with LTM. To this end, we defined two objectives: (1) test if different behavioral and electrophysiological patterns can be distinguished between refreshing and verbal rehearsal, and (2) test whether and how maintaining novel vs. familiar memoranda modulates refreshing at the behavioral and electrophysiological level. We intended to use a task closer to current conceptions and recent behavioral studies, in which continuous maintenance of items in-between a concurrent processing task is required.

We thus conducted an EEG experiment in which we manipulated the maintenance instructions (verbal rehearsal vs. attentional refreshing), the item type (words vs. pseudowords), and the memory load (2 vs. 6) in a modified Brown-Peterson task with serial immediate and free delayed recalls. At the behavioral level, we anticipated better recall performance at short-term when using verbal rehearsal compared to refreshing, while refreshing was expected to benefit more long-term recall than verbal rehearsal. If

pseudowords can be refreshed, we should observe the same behavioral pattern as for words. Conversely, if pseudowords cannot be refreshed, the refreshing instruction should lead to a drastic performance decrease at short-term, and no benefit at long-term. While we expected memory load to modulate the oscillatory activity of the midline-frontal theta and occipito-parietal alpha oscillations because of their links to WM maintenance, the scarce literature did not allow us to make specific hypotheses on the effect of instructions or item type on oscillatory brain activity. Because verbal rehearsal and refreshing have distinct effects on the concurrent processing task (Vergauwe et al., 2014), we also conducted exploratory analyses on ERPs evoked by the processing of the digits during the concurrent parity task and expected different patterns depending on the maintenance instructions and/or memory load.

## **Material & Methods**

### **Participants**

Prior to data collection, an a priori sample size of 30 participants was selected. Previous studies were not similar enough to provide a good estimate of the expected effect size for our main factor of interest, namely the maintenance instructions given to participants. We therefore chose a sample size slightly larger than is usually done in EEG studies on WM. For instance, the systematic review by Pavlov and Kotchoubey (2022) shows an average of 17.93 participants in the 19 studies reporting theta and alpha oscillations during WM maintenance using EEG.

We recruited 30 young adults (26 females) for this experiment. Participants had to be aged between 18 and 30 years old ( $M_{age} = 22$ ,  $SD = 2.5$ ), be native French speakers, be right-handed, and not report substance use or any history of neurological and reading problems. Right-handedness was confirmed using the Edinburg handedness assessment (Oldfield, 1971). Three additional participants were initially recruited but had to be discarded due to technical problems ( $n = 2$ ) or for not completing the experiment ( $n = 1$ ) and are not included in this

report. Participants were compensated 30€ for their participation. The experiment was approved by the ethics committee of Université de Lyon and was conducted in accordance with the declaration of Helsinki, and all participants provided written informed consent before taking part in the study.

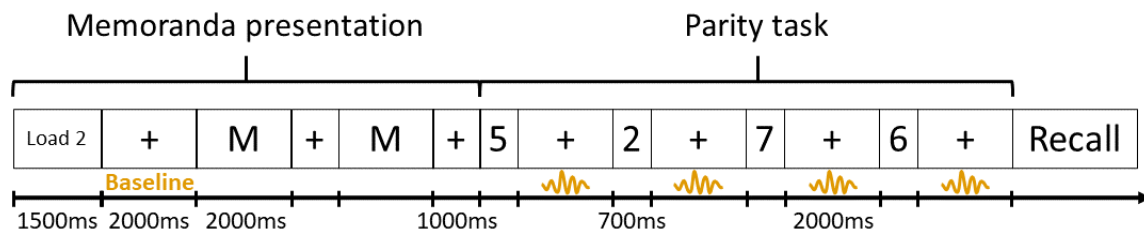
### **Material**

The memoranda list comprised 416 french words and 416 pseudowords. Words were randomly selected from the Lexique3 database (New et al., 2001) using the following criteria: singular common nouns, frequency superior to 50 written occurrences per million, four to eight letters, and one to two syllables long. Pseudowords were generated from the word list using the Wuggy software (Keuleers & Brysbaert, 2010), imposing the same syllable lengths, word lengths, and syllable transition frequencies than the word list.

### **Procedure**

Each trial (Figure 1) began with a screen announcing the memory load (2 or 6 memoranda) of the trial for 1500 ms, followed by a 2000 ms fixation cross. The memoranda could be words or pseudowords depending on the block, and were visually presented sequentially for 2000 ms each at the center of the screen, separated by a 1000 ms inter-item fixation cross. After the presentation of the last to-be-remembered item, the parity task began after a 1000 ms fixation cross. Each of the four digits was presented for 700 ms and followed by a 2000 ms fixation cross. For each digit, participants had to indicate if it was odd or even using the keyboard (*q* for odd, *m* for even on an Azerty keyboard), with both speed and accuracy being stressed in the given instructions. After the last fixation cross, a “Recall” screen indicated to the participant that they had to recall all the memoranda in their original order of presentation on a response sheet with numbered serial positions, without a time limit. Participants were informed that a serial recall was expected, but if the position of an item was

forgotten, they were given the option of recalling it in a free recall box to avoid having to guess a serial position. The next trial began by pressing the space bar.



**Figure 1.** Representation of a trial in the experimental task with a memory load of two. *M* represents a memorandum, which could be a word or pseudoword depending on the condition. Yellow waves indicate the period used for time-frequency analyses.

At the end of a block, participants were asked to count backward by threes for one minute aloud, starting from 700 on the first block and then resuming their progression on the following blocks (the experimenter prompted them the starting number). Accuracy was monitored and participants were asked to correct themselves immediately in case of error. Participants who reached 1 before the end of the experiment were asked to start again at 700. After this distracting task, participants proceeded to the delayed recall, in which they were asked to freely recall a maximum of memoranda from the last block on a blank sheet. This recall ended on participant's request or if no new item was recalled for one minute.

Each participant completed two experimental sessions (one for each maintenance instruction), the second session always taking place between 24 to 48 hours after the first. The first session started with a training followed by the experimental task, while the second session contained only the experimental task. Each session comprised four blocks of 26 trials, for a total of 208 trials per participant over the two sessions.

Participants were given a maintenance instruction at the beginning of a session (verbal rehearsal or refreshing), that they had to use for the entire session. The verbal rehearsal instruction asked participants to silently repeat the words or pseudowords in their heads

between verbal items and between digits<sup>1</sup>. The refreshing instruction asked them to briefly think back to each word or pseudoword, but without verbally saying them in their head, between memoranda and between digits<sup>2</sup>. Emphasis was placed on the importance of complying with these instructions, even if it did not seem efficient to them. The starting instruction was counterbalanced between participants, and the other maintenance instruction was given at the beginning of the second session. Participants were also informed that they had to recall all the words or pseudowords at their positions of presentation, using the numbered lines on the response sheet.

The initial training was divided into two phases. The first phase comprised 54 digits to practice the parity task without time restrictions. The second phase consisted of four trials similar to the experimental task, presenting one trial for each combination of item type and memory load conditions in which the participant had to use the maintenance instruction given for the first session.

In sum, we manipulated the memory load (2 vs. 6), the item type (words vs. pseudowords), and the maintenance instruction (verbal rehearsal vs. refreshing). All variables were manipulated within-subject. The maintenance instruction changed between experimental sessions (four blocks per session), the item type alternated between blocks, and the memory load was pseudo-randomly manipulated between trials. Four versions of the task were created, changing the memory load and item type order, and randomizing the items and digits lists.

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<sup>1</sup> The exact instruction reads as follows (translated from French): “To ensure you don't forget the words/pseudowords, you are instructed to use verbal repetition by repeating them silently in your head between each word/pseudoword presented and between the digits.”

<sup>2</sup> The exact instruction reads as follows (translated from French): “To ensure you don't forget the words/pseudowords, you are instructed to ‘redirect your attention’ to the words/pseudowords presented to you during the series. Do not say the words (do not repeat the words in your head), but think about each word briefly, going over them once or several times between each word and between each digit.”



## **Data Collection, Preprocessing, and Analysis**

### ***Data collection***

For behavioral data, we collected responses to the memory task and the parity judgment task. Immediate recall scoring was calculated as the percentage of words or pseudowords correctly recalled in their position of presentation (i.e., in the correct numbered position on the response sheet). Relative order was not considered when judging correctness (e.g., items 1, 2, and 3 recalled in positions 2, 3, and 4 would be incorrect). Delayed recall was scored as the percentage of items from the block correctly recalled without considering positions. Regarding the parity task, we collected the accuracy as the percentage of correctly judged digits, with answers being accepted only between digit onset and offset, and the response time as the time elapsed between digit's onset and participant's response for correct responses.

Continuous EEG was recorded using a BrainAmp amplifier system (BrainProducts, Germany) from 64 Ag/AgCl active scalp electrodes (ActiCap system). Electrodes were placed according to the extended International 10-20 system (Oostenveld & Praamstra, 2001). The ground electrode was placed between Fp1 and Fp2. One additional electrode was placed on the right mastoid for signal referencing, and four electrooculogram electrodes were placed on the outer canthus of each eye and above and below the right eye to measure horizontal and vertical eye movements and blinks. EEG signal was recorded on-line using BrainVision Recorder at 500 samples per second, with electrodes impedance under 50 k $\Omega$ . Participants were tested individually in a quiet testing room. They were instructed to minimize movements, muscle tension, and blinking during memoranda presentation and during the parity task, but could move and blink freely during recalls.

### *EEG preprocessing*

Preprocessing, time-frequency decomposition, and ERP calculations were done using Brainstorm (Tadel et al., 2011, 2019). Time-frequency and ERP data were then exported and statistical analyses were performed using R (R Core Team, 2019) and the afex package (Singmann et al., 2023) in R Studio (RStudio Team, 2021).

A band-pass (lower cutoff: 1 Hz; upper cutoff: 70 Hz) and a notch filter (50 Hz) were applied on all recordings. Bad electrodes were removed and interpolated for each participant and each experimental session independently using visual inspection of the signal and the Welsch's Power Spectrum Density. Blinks were automatically detected based on the EOG electrodes, allowing to compute an SSP projector used to correct the EEG signals. Correct cleaning of eye blinks was confirmed by visual inspection.

Automatic artifact detection was performed on each trial (from memory load announcement to the beginning of recall) and electrode individually to detect amplitude changes over 100  $\mu$ V. A trial was rejected if such a change happened during the baseline or the maintenance periods (see below). If one electrode was responsible for the rejection of more than 10% of the trials for one recording session of a participant, it was marked as bad for all trials of this participant's session and interpolated, then the artifact detection was performed again.

For the time-frequency analyses, the baseline and the four maintenance periods were then extracted from each trial. To avoid oscillatory activities related to encoding preparation that appear around 200 or 300 ms prestimulus (Addante et al., 2011; Guderian et al., 2009) and activities linked to the following presentation and processing of the stimulus, the baseline was defined as the central 1000 ms of the 2000-ms initial fixation cross. Additionally, we controlled that the baseline power did not significantly differ between the conditions of item type and maintenance instruction. The maintenance periods were extracted from the free-time

windows between digits (i.e., the fixation crosses between digits), where WM maintenance is thought to occur (e.g., Barrouillet et al., 2004), removing 350 ms from the beginning and the end of each period (central 1300 ms used) to avoid processing-related activity. The encoding phase (i.e., memoranda's presentation and between-items free time) was not analyzed. Time-frequency power maps were calculated for the maintenance and baseline periods independently using Morlet wavelets (1-70 Hz, step 1 Hz; the family of Morlet wavelets was designed so that the wavelet centered at 1Hz and had a FWHM of 3 seconds) for each trial and then averaged separately for each participant and condition, with the option to remove the evoked response from the Brainstorm toolbox. Each averaged time-frequency map was then baseline-normalized using Z scores. Normalized time-frequency maps were exported to R for statistical analyses.

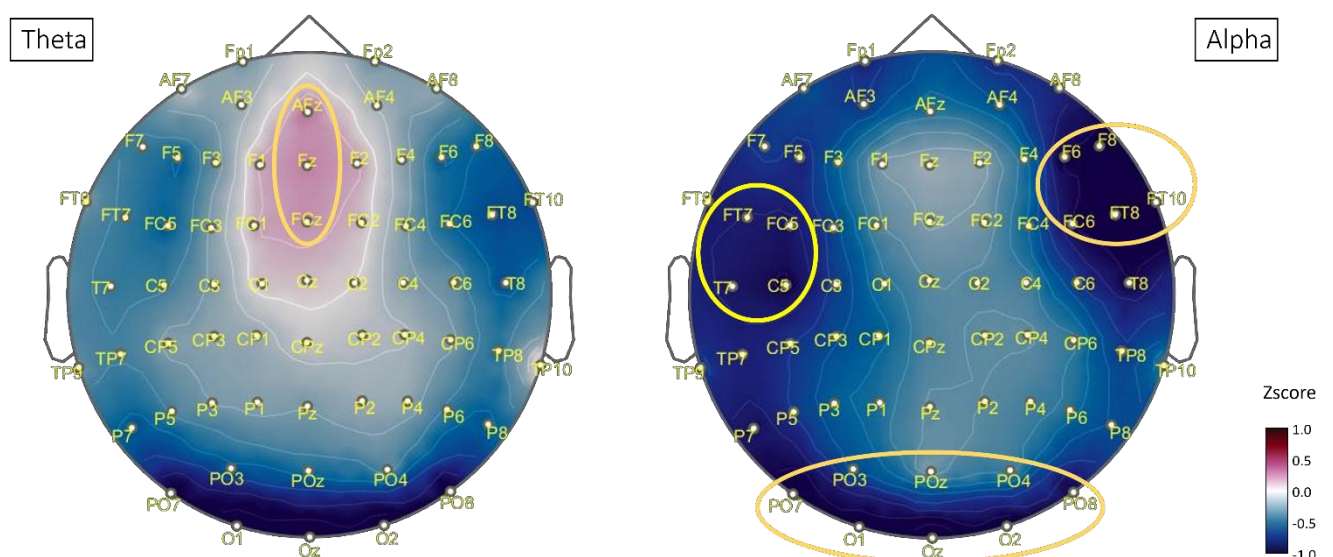
For ERPs, a band-pass filter (1-20Hz) was applied to the continuous recordings. Trials were then epoched into processing windows, starting at the onset of the to-be-processed digit, and encompassing the whole 2000-ms maintenance window after digit offset. Epochs were averaged to obtain the ERPs for each condition of memory load, maintenance instruction, and item type, and were then baseline-corrected by removing the mean of the baseline. The baseline was set to the same time window as for the time-frequency analyses.

### ***Statistical analyses***

*Behavioral analyses.* Independent ANOVAs were conducted on the percentage of correct immediate recall, the percentage of correct delayed recall, the percentage of correct responses to the parity task and averaged response time to the parity task. Each of these ANOVAs used memory load, maintenance instructions, and item type as predictors. Effect sizes were reported using  $\eta^2_G$  (generalized eta-squared; Olejnik & Algina, 2003), which provides better comparability between designs than partial eta-squared (Bakeman, 2005). Significant interactions were interpreted with simple-effect analyses using t-tests.

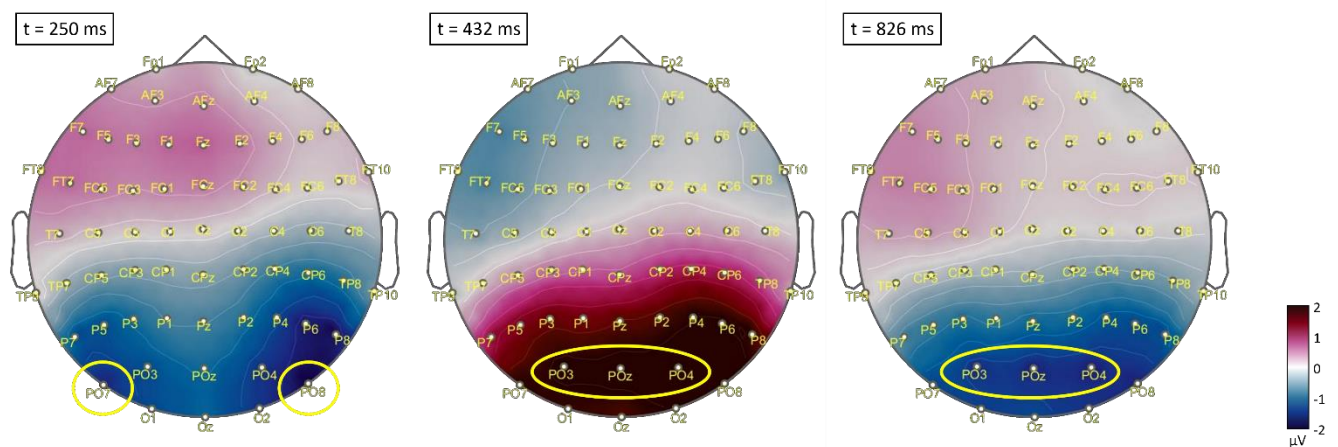
*TF analyses.* Following the literature, we planned to analyze frontal-midline theta in the 4-8 Hz band put forward by Hsieh & Ranganath (2014) and an occipital-parietal alpha in the 9-12 Hz band (Hsieh et al., 2011; Jensen et al., 2002; Roberts et al., 2013). These Regions Of Interest (ROIs) were further delineated by a spatial cartography of averaged power across all conditions in the alpha and theta bands during the maintenance period (Figure 2). For the theta band, we selected a frontal-midline ROI including the Fz, AFz, and FCz electrodes. For the alpha band, we selected an occipito-parietal ROI including the Oz, O1, O2, PO7, PO3, POz, PO4, and PO8 electrodes, a right fronto-temporal ROI including the F6, F8, FC6, FT8, and FT10 electrodes, and a left fronto-temporal ROI including the FT7, FC5, T7, and C5.

Oscillatory power was averaged by subject and experimental condition over selected ROIs, frequency bands, and time (i.e., across the selected time window). As for behavioral analyses, ANOVAs were conducted on each frequency band (theta or alpha) and ROI independently, with memory load, maintenance instructions, and item type as predictors.



**Figure 2.** Spatial cartography for theta (4-8 Hz; left) and alpha (9-12 Hz; right) oscillations. Baseline-corrected (z-score) oscillatory power in each of the two frequency bands of interest, averaged over subjects and conditions during the maintenance periods (central 1350 ms of the inter-digits fixation crosses, see Figure 1). Yellow circles reflect the chosen regions of interest.

*ERP analyses.* As an exploratory analysis, ERPs evoked by the processing of the digits were also analyzed to observe whether they were modulated by the kind of item and maintenance strategy. Electrodes and time-windows were selected a posteriori based on data. Figure 3 depicts the spatial cartography for the three posterior ERPs identified during the concurrent processing of the digits. We selected the PO7 and PO8 electrodes for the analysis of the first ERP (negative peak at 250 ms: analyzed in the 206-306 ms time-window, maximum at 250 ms), and the PO3, POz, and PO4 electrodes for the two following ERPs (positive peak at 480 ms: analyzed on 380-590 ms, maximum at 478 ms; negative peak at 800 ms: analyzed on 724-874 ms, maximum at 826 ms). Each ERP was analyzed by averaging ERP amplitude across the analysis time-window separately by item type, maintenance instruction, and memory load and conducting an ANOVA as for behavioral data and TF power (see above)



**Figure 3.** Spatial cartography of the three identified posterior ERPs following digits presentation. The maximum amplitude of ERPs is at 250 ms, 432 ms, and 826 ms respectively relative to the onset of the to-be-processed digit. Yellow circles indicate the selected electrodes.

## Results

### **Analyses of memory and maintenance**

The main analyses consisted of analyses of immediate and delayed recalls, and oscillations power in theta and alpha frequency bands during working memory maintenance. Supplementary analyses of behavioral data to control for methodological factors are presented in Appendix 1. All participants reported having complied with the given maintenance instructions after each session. An analysis was performed to evaluate the session order, specifically to determine if there were any carryover effects between instructions sessions. The results revealed no evidence of such effects. Additionally, as one and two-syllables long memoranda were included, we also analyzed the effect of the number of syllables on short-term and long-term recall. Presentation of the items was counterbalanced, so that one and two-syllables items were presented equally in all conditions overall, except between the memory load conditions which had a different total number of items presented and thus could not be equated. Results show a significant effect of the number of syllables on both kind of recall for pseudowords only, but no interaction with any of the other factors, supporting an absence of confound with the manipulated factors.

### ***Recall performance***

To limit the effects of perceptive and orthographic errors, the recall scores included a tolerance of one mistake on each word or pseudoword (i.e., addition, omission, or substitution of one letter), similar to previous studies using pseudowords (Kowialiewski & Majerus, 2018; Labaronne, Jarjat, et al., 2023; Moore et al., 2010). Four ANOVAs were conducted independently on words and pseudowords immediate and delayed recall scorings, with memory load, maintenance instructions, and item type as predictors. Effect sizes were reported using  $\eta^2_G$ . Unreported effects were not significant ( $p > .10$ ). A complementary

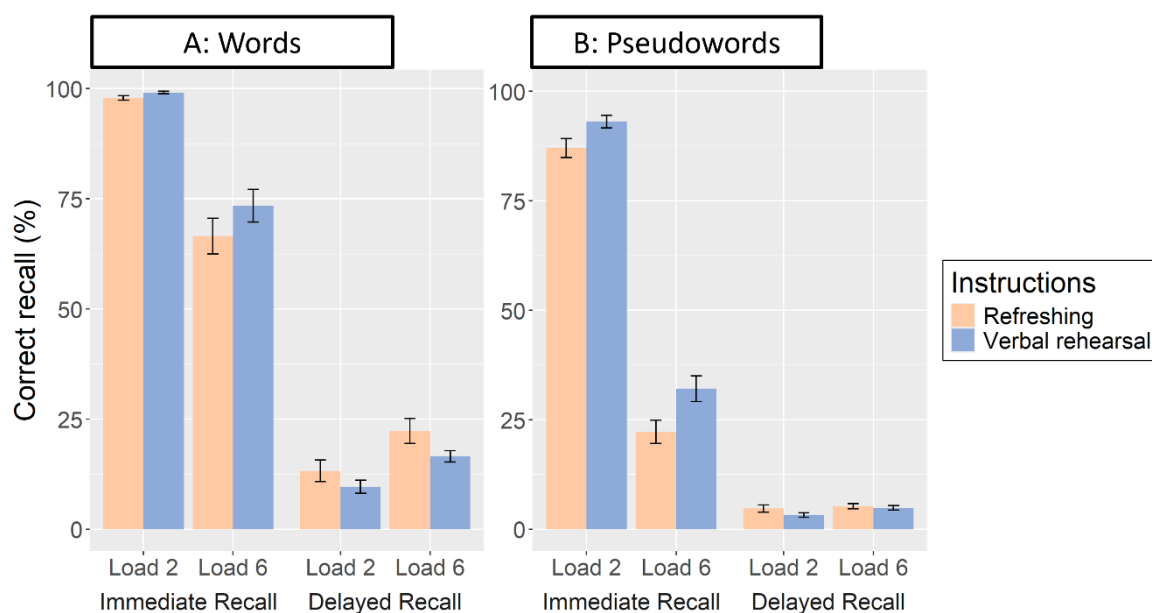
analysis on free recall scoring, that did not consider items' serial position, was conducted and led to results very similar to immediate serial scoring (Appendix 2).

Immediate and delayed recall performance for words and pseudowords is presented in Figure 4. At immediate recall, we observed a main effect of maintenance instructions with better performance when using verbal rehearsal ( $M = 63.58\%$ ;  $SD = 13.85$ ) rather than refreshing ( $M = 56.39\%$ ;  $SD = 13.38$ ),  $F(1, 29) = 15.14$ ,  $p < .001$ ,  $\eta^2_G = .045$ , and a significant instructions  $\times$  item type interaction,  $F(1, 29) = 5.23$ ,  $p = .030$ ,  $\eta^2_G = .005$ . However, given that there appears to be a ceiling effect for words in the condition of memory load 2, we conducted a post-hoc test to verify if the instruction  $\times$  item type interaction could still be observed when considering only memory load 6 trials. Even in the absence of an instructions  $\times$  item type  $\times$  memory load interaction, this test seems important to correctly interpret the instructions  $\times$  item type interaction. Indeed, we observed that the instructions  $\times$  item type interaction was significant with a memory load of 2 ( $F(1, 29) = 5.82$ ,  $p = .022$ ) but not of 6 ( $F(1, 29) = 1.03$ ,  $p = .31$ ), suggesting that the instructions  $\times$  item type interaction results from the ceiling effect with words and should not be interpreted. Unsurprisingly, we found a main effect of item type with better recall for words ( $M = 77.08\%$ ;  $SD = 14.17$ ) than for pseudowords ( $M = 42.88\%$ ;  $SD = 12.08$ ),  $F(1, 29) = 392.30$ ,  $p < .001$ ,  $\eta^2_G = .461$ . Additionally, recall was better under low ( $M = 94.28\%$ ;  $SD = 4.75$ ) than high ( $M = 48.55\%$ ;  $SD = 15.43$ ) memory load,  $F(1, 29) = 376.35$ ,  $p < .001$ ,  $\eta^2_G = .732$ . The memory load effect was significant for both words ( $t(29) = 8.62$ ,  $p < .001$ ) and pseudowords ( $t(29) = 32.21$ ,  $p < .001$ ), but larger for pseudowords (+62.91) than words (+28.55) as revealed by the item type  $\times$  memory load interaction ( $F(1, 29) = 161.19$ ,  $p < .001$ ,  $\eta^2_G = .278$ ). Again, this interaction probably reflects the ceiling effect when in the conditions with two words.

At delayed recall, we found a similar effect of item type than at immediate recall,  $F(1, 29) = 54.66$ ,  $p < .001$ ,  $\eta^2_G = .295$ . The effect of memory load was reversed compared to

immediate recall, with better performance under high ( $M = 12.25\%$ ;  $SD = 5.83$ ) than low ( $M = 7.74\%$ ;  $SD = 5.39$ ) memory load,  $F(1, 29) = 50.14$ ,  $p < .001$ ,  $\eta^2_G = .067$ . Again, the effect of memory load was significant for both words ( $t(29) = -6.39$ ,  $p < .001$ ) and pseudowords ( $t(29) = -3.31$ ,  $p = .002$ ), but was larger for words (+4.95) than pseudowords (+1.07) as indicated by the item type  $\times$  memory load interaction ( $F(1, 29) = 28.20$ ,  $p < .001$ ,  $\eta^2_G = .040$ ). Interestingly, contrary to immediate recall, delayed recall was better when using refreshing ( $M = 12.59\%$ ;  $SD = 8.58$ ) compared to verbal rehearsal ( $M = 9.66\%$ ;  $SD = 3.90$ ),  $F(1, 29) = 4.55$ ,  $p = .042$ ,  $\eta^2_G = .027$ . The significant instructions  $\times$  item type interaction,  $F(1, 29) = 4.72$ ,  $p = .038$ ,  $\eta^2_G = .012$ , indicated that the effect of instructions was observed for words (+5.19;  $t(29) = 2.21$ ,  $p = .034$ ) but not pseudowords (+0.67;  $t(29) = 1.32$ ,  $p = .195$ ), with however a floor effect for pseudowords (see Figure 4B).

In summary, the main findings are that for words, immediate recall was higher when using verbal rehearsal than refreshing, while delayed recall was higher when using refreshing than verbal rehearsal. For pseudowords, immediate recall was also better when using verbal rehearsal, but no effect of instructions was observed in delayed recall, due in part to a floor effect.





**Figure 4.** Percentage of correct immediate serial and delayed free recall for words (panel A) and pseudowords (panel B) by memory load, item type, and maintenance instruction. Error bars represent the standard error.

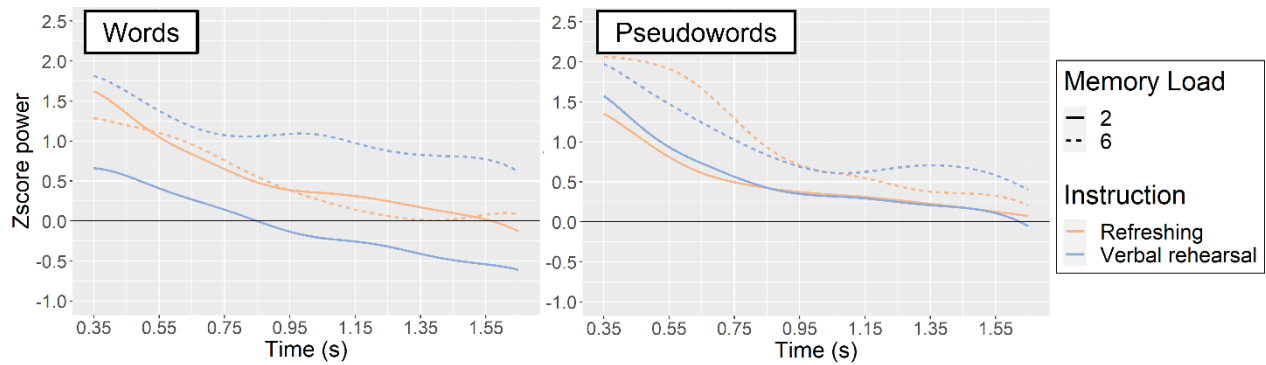
### *Frontal-midline theta*

Frontal-midline theta power throughout the maintenance period is illustrated in Figure 5. We used a t-test against 0 to evaluate if averaged theta power during maintenance increased compared to the baseline. This effect was significant,  $t(29) = 2.51$ ,  $p = .018$ , with a mean Z score power of 0.59 over the maintenance period.

We observed a main effect of memory load on mean theta power during the maintenance period,  $F(1, 29) = 14.75$ ,  $p < .001$ ,  $\eta^2_G = .02$ . Critically, the memory load  $\times$  item type  $\times$  instructions interaction was significant,  $F(1, 29) = 6.86$ ,  $p = .014$ ,  $\eta^2_G = .008$ . Its decomposition showed that the memory load  $\times$  instructions interaction was significant for words,  $t(29) = 2.66$ ,  $p = .012$ , but only the simple effect of memory load was significant for pseudowords,  $t(29) = 2.36$ ,  $p = .024$ , with stronger power for 6 memoranda than for 2. The decomposition of the memory load  $\times$  instructions interaction for words showed that the effect of memory load was significant when using verbal rehearsal,  $t(29) = -4.09$ ,  $p < .001$ , but not refreshing ( $t(29) = 0.07$ ,  $p = .94$ )<sup>3</sup>, with a stronger power when maintaining 6 memoranda compared to 2 (as for pseudowords under both maintenance instructions). Overall, this interaction shows that memory load modulated theta power (6 items > 2 items) for pseudowords. For words, this effect was also present when using verbal rehearsal, but not refreshing.

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<sup>3</sup> For reference, this effect was also tested the other way around (i.e., the effect of instruction depending on the memory load condition for words). The result shows that the effect of instructions trended toward significance both for a memory load of 2,  $t(29) = 1.86$ ,  $p = .07$ , and a memory load of 6,  $t(29) = -1.92$ ,  $p = .06$ . This suggests that theta power under refreshing instructions is higher than when rehearsing for two words, and lower than when rehearsing for six words.



**Figure 5.** Mean theta Z score power over the frontal-midline site (AFz, Fz, Cz) through the analyzed maintenance period (0.35s-1.65s after disappearance of the digit of the concurrent processing task) for words (left panel) and pseudowords (right panel), by memory load and maintenance instruction. Time 0 corresponds to the digit disappearance.

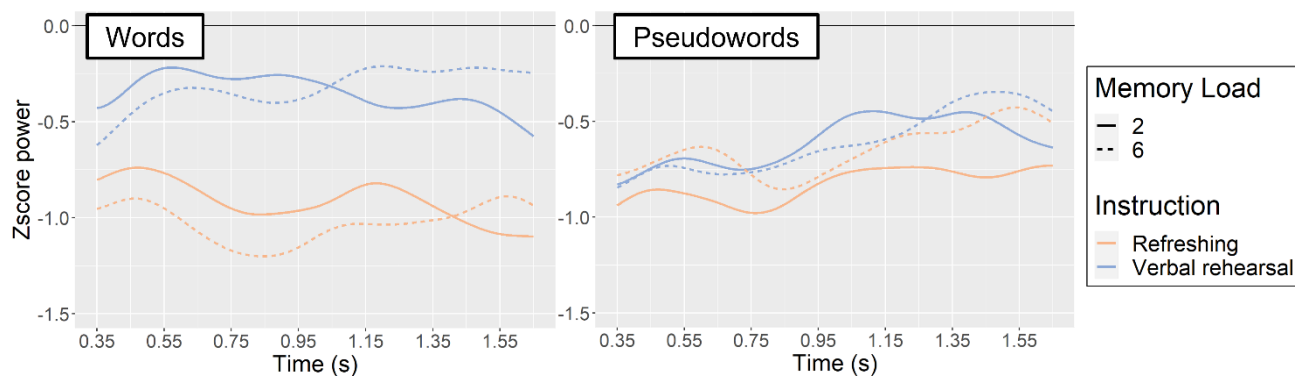
### ***Occipito-parietal alpha***

Occipito-parietal alpha power throughout the maintenance period is illustrated in Figure 6. Mean alpha power significantly decreased during maintenance compared to baseline,  $t(29) = -2.83$ ,  $p = .008$ ,  $M = -0.67$ .

We found a main effect of instructions on mean alpha power during maintenance,  $F(1, 29) = 4.33$ ,  $p = .046$ ,  $\eta^2_G = .016$ , with a stronger desynchronization under refreshing than verbal rehearsal. The instructions  $\times$  item type interaction was significant,  $F(1, 29) = 4.47$ ,  $p = .043$ ,  $\eta^2_G = .006$ . The simple-effect analysis of this interaction showed that the effect of instructions was significant for words with a stronger desynchronization under refreshing than verbal rehearsal instructions,  $t(29) = -2.72$ ,  $p = .010$ , but not for pseudowords ( $t(29) = -0.79$ ,  $p = .43$ ).

As we found an effect of the maintenance instruction and item type, we tested again if alpha power was significantly different from 0 using post-hoc t-tests, this time distinguishing each combination of instruction and item type. The difference was not significant when using verbal rehearsal with words ( $t(29) = -1.13$ ,  $p = .27$ ) and trended toward significance with pseudowords ( $t(29) = -1.88$ ,  $p = .07$ ). When using refreshing, the difference was significant

with both words ( $t(29) = -4.40, p < .001$ ) and pseudowords ( $t(29) = -3.68, p < .001$ ).



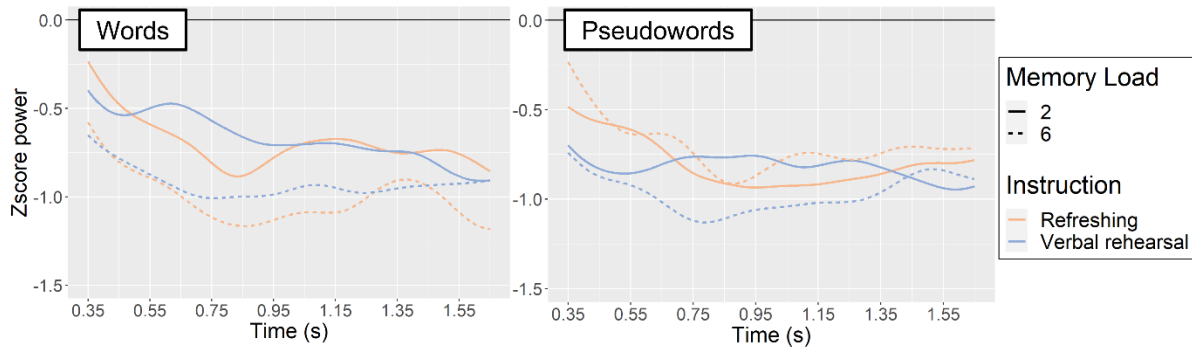
**Figure 6.** Mean alpha Z score power over the occipito-parietal site ( $Oz, O1, O2, PO7, PO3, POz, PO4, PO8$ ) through the analyzed maintenance period (0.35s-1.65s after disappearance of the digit of the concurrent processing task) for words (left panel) and pseudowords (right panel), by memory load and maintenance instruction. Time 0 corresponds to the digit disappearance.

### ***Right fronto-temporal alpha***

No main effect or interaction was significant in this region (all  $ps > .10$ ). We conducted a t-test against 0 to verify if the mean Z score power changed significantly during maintenance compared to baseline, and concluded that the alpha power decreased ( $M = -0.89$ ) during maintenance,  $t(29) = -5.22, p < .001$ .

### ***Left fronto-temporal alpha***

A t-test against 0 indicated that the mean Z score power decreased significantly in this region during maintenance,  $t(29) = -5.15, p < .001$  (Figure 7). No effect was significant in this region (all  $ps > .10$ ), with only the memory load  $\times$  item type interaction that trended toward significance,  $F(1, 29) = 3.33, p = .078, \eta^2_G = .003$ . Simple-effect analysis on this interaction indicates that the effect of memory load trended toward significance for words,  $t(29) = 2.03, p = .051$ , but not pseudowords ( $p = .81$ ).



**Figure 7.** Mean alpha Z score power over the left fronto-temporal site (FT7, FC5, T7, C5) through the analyzed maintenance period (0.35s-1.65s after disappearance of the digit of the concurrent processing task) for words (panel A) and pseudowords (panel B), by memory load and maintenance instruction. Time 0 corresponds to the digit disappearance.

### **Brain-behavior correlations**

To estimate how oscillations are linked with memory performance, we conducted correlations between immediate and delayed recall performance and frontal-midline theta and occipito-parietal alpha power. Given that there were ex-aequo in memory performance levels, correlations were analyzed using Kendall's Tau. For both immediate and delayed recall, correlations were calculated between averaged memory performance and averaged alpha or theta power, for each condition of memory load, instruction, and item type independently.

At immediate recall, because of a ceiling effect in the memory load 2 conditions, these correlations were conducted only in the memory load 6 conditions. Occipito-parietal alpha power negatively correlated with immediate serial recall performance when verbally rehearsing words ( $\tau = -0.30, p = .020$ ) and pseudowords ( $\tau = -0.29, p = .024$ ), and trended toward significance when refreshing words ( $\tau = -0.21, p = .097$ ). Occipito-parietal alpha power did not significantly correlate with delayed recall performance.

Frontal-midline theta power did not correlate with either immediate serial recall or delayed recall in any of the conditions, with only the correlation with delayed recall when verbally rehearsing words that trended toward significance ( $\tau = -0.22, p = .093$ ).

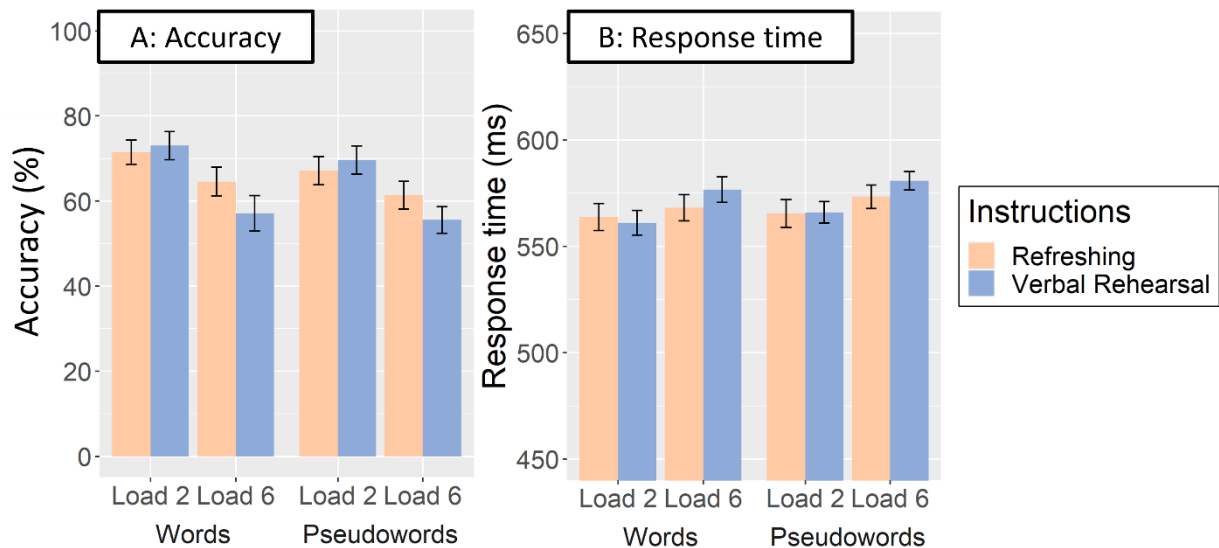
## Analyses of the processing task

It is thought that the maintenance and processing components of working memory are in competition for attentional resources (Barrouillet et al., 2004, 2007), resulting in a differential impact of verbal rehearsal and refreshing on the concurrent processing task (e.g., Vergauwe et al., 2014). Thus, we conducted complementary analyses on performance in the concurrent parity task and the ERPs evoked by the processing of the digits to further characterize the distinction between these two maintenance mechanisms.

### *Parity task performance*

We first analyzed accuracy on the parity task (Figure 8A). We conducted an ANOVA on the mean percentage of correct response with memory load, item type, and maintenance instructions as predictors. There was a main effect of item type,  $F(1, 29) = 8.89, p = .006, \eta^2_G = .007$ , with better performance on the parity task when concurrently maintaining words ( $M = 66.55\%; SD = 17.29$ ) than pseudowords ( $M = 63.44\%; SD = 15.94$ ). Additionally, there was a main effect of memory load,  $F(1, 29) = 84.74, p < .001, \eta^2_G = .080$ . The memory load  $\times$  instructions interaction was significant,  $F(1, 29) = 29.92, p < .001, \eta^2_G = .014$ , and the simple effect of instructions (refreshing  $>$  verbal rehearsal) was significant with a memory load of 6 (verbal rehearsal:  $M = 56.33\%, SD = 19.18$ ; refreshing:  $M = 63.00\%, SD = 17.23$ ),  $t(29) = 2.87, p = .007$ , but not of 2 ( $t(29) = 1.05, p = .29$ ).

A similar analysis was conducted on response time for correct responses only (Figure 8B). We found a main effect of memory load,  $F(1, 29) = 71.61, p < .001, \eta^2_G = .034$ . The memory load  $\times$  instructions interaction was significant,  $F(1, 29) = 14.06, p < .001, \eta^2_G = .007$ , indicating that the effect of instructions (longer response time with verbal rehearsal) was significant with a memory load of 6 (verbal rehearsal:  $M = 578.57$  ms,  $SD = 26.60$ ; refreshing:  $M = 570.57$  ms,  $SD = 30.93$ ;  $t(29) = -2.60, p = .014$ ), but not with a memory load of 2 ( $t(29) = 0.35, p = .72$ ).



**Figure 8.** Mean accuracy (panel A) and response time (panel B) in the concurrent parity task by maintenance instructions, item type, and memory load. Data for the response time includes only correct responses. Error bars represent the standard error.

### ***Event-related potentials***

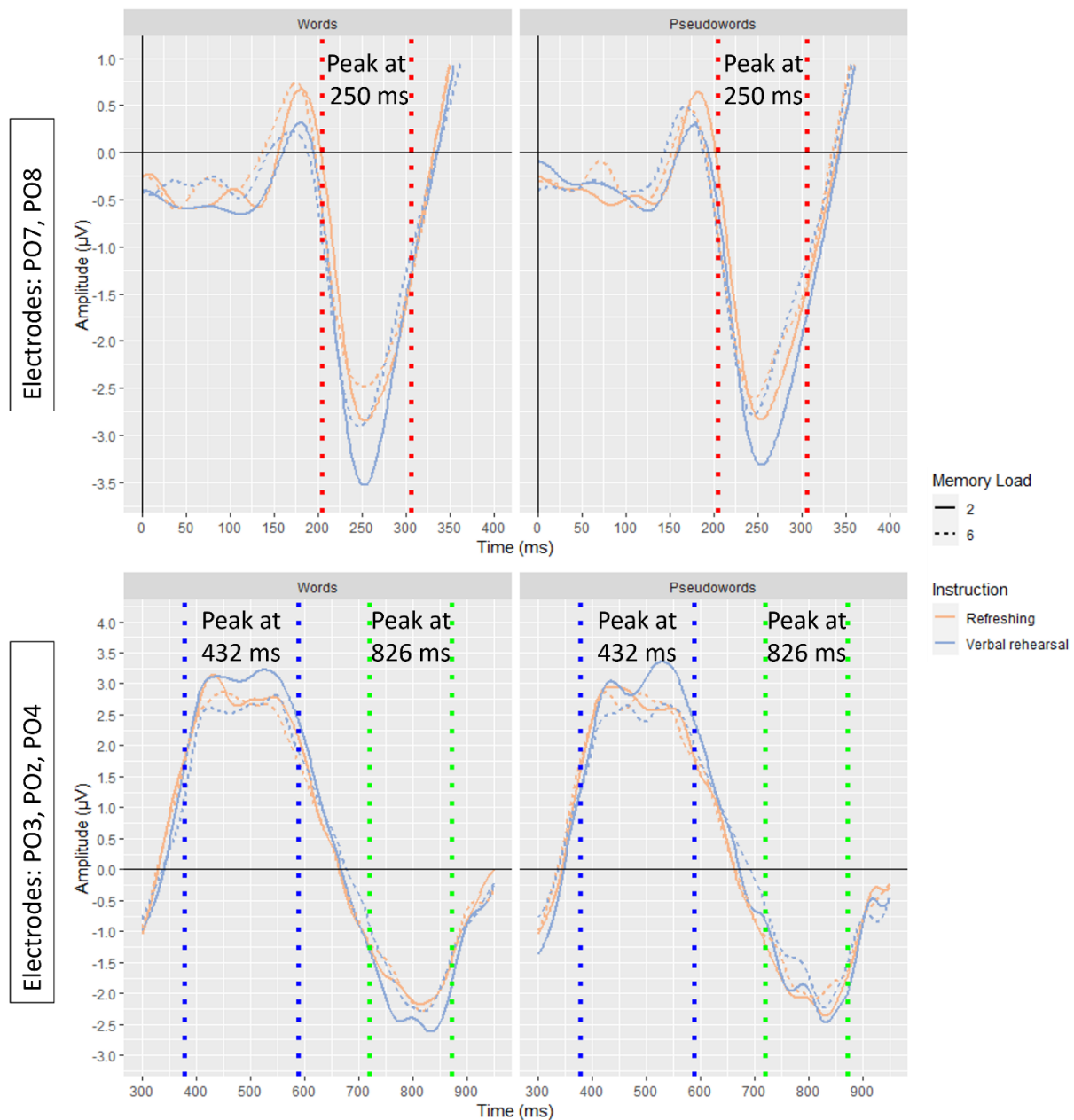
We analyzed ERPs (Figure 9) during digit processing and the following maintenance period. Three ERPs of interest were chosen a posteriori based on data: a negative ERP (minimum at 250 ms; PO7 and PO8 electrodes), a positive ERP (maximum at 432 ms; PO3, POz, and PO4 electrodes), and a negative ERP (minimum at 826 ms; PO3, POz, and PO4 electrodes).

For the negative ERP at 250 ms, we found a main effect of memory load,  $F(1, 29) = 7.75, p = .009, \eta^2_G = .005$ , and a memory load  $\times$  instruction interaction,  $F(1, 29) = 7.11, p = .012, \eta^2_G = .003$ . Decomposition of the interaction indicates a simple effect of memory load under verbal rehearsal instruction (larger amplitude with 2 items;  $t(29) = 3.24, p = .003$ ) but not under refreshing instruction ( $t(29) = 0.75, p = .45$ ).

Similarly on the positive ERP at 432 ms, we observed a main effect of memory load,  $F(1, 29) = 10.05, p = .004, \eta^2_G = .005$ , and a memory load  $\times$  instruction interaction,  $F(1, 29) = 14.14, p < .001, \eta^2_G = .002$ . Simple-effect analysis on the interaction indicates a

significant effect of memory load when using verbal rehearsal (larger amplitude with 2 items),  $t(29) = 3.76, p < .001$ , but not refreshing ( $t(29) = 1.38, p = .17$ ).

For the negative ERP at 826 ms, we observed a main effect of memory load,  $F(1, 29) = 6.57, p = .016, \eta^2_G = .009$ , and an item type  $\times$  instruction interaction,  $F(1, 29) = 4.57, p = .041, \eta^2_G = .003$ . The main effect of item type trended toward significance,  $F(1, 29) = 4.27, p = .097, \eta^2_G = .002$ . Simple-effect analysis on the item type  $\times$  instruction interaction indicates a significant effect of item type (larger amplitude with words) when using verbal rehearsal,  $t(29) = 2.31, p = .027$ , but not refreshing ( $t(29) = 0.33, p = .74$ ). The memory load  $\times$  instruction interaction was significant,  $F(1, 29) = 4.57, p = .048, \eta^2_G = .003$ . Its decomposition indicates a simple effect of memory load (larger amplitude with 2 items) when using verbal rehearsal,  $t(29) = 2.76, p = .009$ , but not refreshing ( $t(29) = 1.45, p = .15$ ).



**Figure 9.** Mean ERPs during digit processing for selected electrodes, by memory load (2 vs. 6), maintenance instruction (refreshing vs. verbal rehearsal) and item type (words vs. pseudowords). Dotted lines indicate time-windows used for analyses. Digit appearance was at 0 ms and disappearance at 700 ms.

## Discussion

We investigated attentional refreshing functioning and its interplay with LTM, by evaluating two questions in particular: the difference between refreshing and verbal rehearsal, and the ability to refresh novel (vs. familiar) memoranda. The key results are that short-term



recall was better when using verbal rehearsal than refreshing for both words and pseudowords, whereas long-term recall was better when using refreshing than verbal rehearsal but mostly for words. Consistently, we observed distinct patterns of frontal-midline theta and occipito-parietal alpha oscillations when comparing refreshing and verbal rehearsal, but only when maintaining words. For pseudowords, the two maintenance instructions led to similar oscillatory activity. ERPs evoked by the digits of the processing tasks further revealed differences between maintenance instructions, with an effect of memory load on ERP amplitude under verbal rehearsal but not refreshing instructions.

### **Independence between attentional refreshing and verbal rehearsal**

Attentional refreshing has been posited to be independent of verbal rehearsal because previous literature suggested different effects on memory and distinct brain networks supporting them (Camos, 2015; Camos et al., 2018; Camos & Barrouillet, 2014). However, although frontal theta and posterior alpha involvement in WM maintenance have been established (review in Pavlov & Kotchoubey, 2022), no study to our knowledge has investigated the specific oscillatory pattern associated with refreshing.

The present results show that using verbal rehearsal led to better memory performance in short-term recall than using refreshing for both words and pseudowords. As our task included a concurrent processing component, this result is consistent with previous observations that verbal rehearsal is more efficient for maintenance than refreshing in case of concurrent attentional demand (Camos & Barrouillet, 2014). Conversely, refreshing benefited delayed recall more than verbal rehearsal for words in line with previous behavioral studies (Camos & Portrat, 2015; Jarjat et al., 2018, 2020). Thus, our behavioral results support distinct effects on memory for the two mechanisms. Similarly, our time-frequency analyses support distinct oscillatory patterns between refreshing and verbal rehearsal. For words, we found that frontal-midline theta power increased with memory load when using verbal

rehearsal but not refreshing. In keeping with the behavioral results indicating that the condition involving rehearsal of two words was the easiest, the increase in frontal-midline theta power was found to be the smallest in this condition. Additionally, occipito-parietal alpha power desynchronization was larger when using refreshing compared to verbal rehearsal, for words. At the same time, we found that memory load modulated the posterior ERPs for the digits of the parity task only with verbal rehearsal, suggesting that concurrent maintenance and processing were handled differently under the two kinds of maintenance. Together, our results support the independence between refreshing and verbal rehearsal (Camos, 2015; Camos et al., 2011; Camos & Barrouillet, 2014; Mora & Camos, 2013).

The involvement of frontal midline theta in WM maintenance was proposed many times in the literature (e.g., Gevins et al., 1997; Jensen & Tesche, 2002; Meltzer et al., 2008; Onton et al., 2005; Scheeringa et al., 2009). Consistently, we observed an increase in theta power during maintenance compared to baseline. Theta activity has been proposed to play a role in the maintenance of temporal relationships between memoranda (Hsieh & Ranganath, 2014; Roberts et al., 2013). As temporal relationships become more complex with the number of memoranda maintained, it is expected that theta power increases with higher memory load. In the present experiment, we replicated the memory load effect on frontal midline power, except when refreshing words. Two contradictory interpretations could be given for this result. Because serial order needs to be maintained with both refreshing and verbal rehearsal, the absence of a memory load effect when refreshing words would go against the temporal order hypothesis and suggest that frontal midline theta plays another role in WM maintenance. Conversely, if we accept the temporal order hypothesis, this result could rather be interpreted as evidence that the number of representations maintained did not increase with memory load when refreshing words, for instance by maintaining a combined representation of all memoranda such as a mental image, which was possible only when refreshing words.

This later view could also be supported by the observation that the amplitude of the occipito-parietal ERPs in response to the parity task were modulated by memory load only when using verbal rehearsal, which could suggest that the effective memory load (i.e., the number of distinct objects maintained by the participants) did not vary with the manipulated memory load when using refreshing. As suggested by Pavlov and Kotchoubey (2022), studies specifically designed to test the temporal order hypothesis will be needed to further discuss this question, and considering the kind of maintenance strategy used and the type of item maintained may be important to this end.

As presented in the introduction, modulation of posterior alpha activity is frequently reported during WM maintenance, reflected by a memory load effect on alpha power. However, the direction of its modulation during maintenance is inconsistent across verbal and visuo-spatial WM studies (Pavlov & Kotchoubey, 2022). In the present study, we did not observe any modulation of posterior alpha with memory load, contrary to previous literature using verbal material (Jensen et al., 2002; Proskovec et al., 2019). However, we observed an alpha suppression over the occipito-parietal site during maintenance. It has been posited previously that alpha oscillations reflect functional inhibition of task-irrelevant regions, and thus alpha suppression reflects active processing in the area (Händel et al., 2011; Jensen & Mazaheri, 2010; Klimesch et al., 2007). Additionally, prioritization in visual WM, resulting from cueing a lateralized item, is accompanied by a contralateral posterior alpha suppression (de Vries et al., 2018; Myers et al., 2015; Rösner et al., 2020), suggesting that active maintenance of a memorandum is reflected by an alpha suppression in the relevant perceptual region. Consistently, short-term storage is thought to take place in perceptual regions (Sreenivasan et al., 2014) and WM maintenance has been shown to reactivate regions linked to the initial perception of the stimulus (M. R. Johnson et al., 2007; M. R. Johnson & Johnson, 2009; Postle et al., 2003). Together, this literature indicates that posterior alpha suppression

can occur when visual areas are actively processing external or internal objects. In the present experiment, our results show an alpha suppression in all conditions, suggesting that posterior areas were recruited for WM maintenance. Across participants, a larger alpha desynchronization was associated with better performance at immediate recall, especially when using verbal rehearsal, further emphasizing the link between the activation of a posterior network and memory performance. This posterior alpha suppression was stronger when using refreshing compared to verbal rehearsal for words, while alpha was similarly suppressed with both instructions for pseudowords. This suggests that for words, visual areas were more recruited when refreshing than when verbally rehearsing, perhaps due to the use of a mental imagery strategy as we will argue later; while visual areas were similarly involved to refresh and to verbally rehearse pseudowords. Another way of looking at our results would be to consider that rehearsing words led to a reduced alpha desynchronization compared to all other conditions, coupled with the observation of a larger amplitude on the N250 and P432 ERPs during the processing task when rehearsing 2 words. This could suggest a reduced maintenance demand when rehearsing words, particularly when rehearsing only two words, compared to all other conditions. Overall, our results support the independence between verbal rehearsal and refreshing, and also suggest that the type of item maintained and the type of maintenance engaged modulate posterior alpha activity during a WM task. This could support the view proposed by van Ede (2018) that the directionality of posterior alpha during a WM task is determined by regions' relevance for maintenance, but this opposition may not be as simple as comparing visual and verbal WM, as maintenance strategies might also be a determining factor.

Direct instructions to refresh have been used previously and gave convincing behavioral (Camos et al., 2011; Souza et al., 2015, 2018) and neuroimaging (M. K. Johnson et al., 2005; M. R. Johnson et al., 2007, 2015; Raye et al., 2002, 2007) evidence that participants

used refreshing when instructed. At the same time, we have shown in previous work that when no maintenance instructions are given, participants rarely self-report using refreshing (Labaronne, Ferreri, et al., 2023). This poor first-person knowledge about refreshing contributes to the difficulty in characterizing this mechanism. Results in the present study can shed new light on its implementation. Because alpha power decrease indicates active engagement of the area (Jensen & Mazaheri, 2010; Jokisch & Jensen, 2007), the posterior alpha suppression we observed when refreshing words, larger than when using verbal rehearsal, could suggest that participants engaged in some form of visual maintenance such as mental imagery. At the same time, the neural distinction between refreshing and verbally rehearsing pseudowords was not so clear, yet the two instructions still had different effects on the short-term recall of pseudowords. Thus, although results for words suggest the use of mental images when refreshing, it may not be the case when refreshing other kinds of material such as pseudowords. For pseudowords, it may instead be that the engagement of visual areas reflects that a visual representation is necessary for both verbal rehearsal and refreshing, because the spelling cannot be retrieved from LTM. We will return to this issue later on.

Another significant question concerns the fact that if participants indeed relied on mental imagery under the refreshing words instruction, there is a difference in the sensory modality involved to maintain the words that may drive, at least in part, the observed differences in activations between the two instructions. In other words, is refreshing a phonological representation equal to verbally rehearsing it? Future studies should examine whether the distinction between these two maintenance mechanisms stands when they can rely on the same sensory modality, for instance both maintaining auditory stimuli.

### **Refreshing novel memoranda**

Some previous literature suggested that refreshing could not be used to maintain novel or unfamiliar memoranda (Loaiza et al., 2015; Nees et al., 2017; Ricker & Cowan, 2010;

Vergauwe et al., 2014), leading to the proposition that refreshing may need LTM traces to operate. However, recent results showed that the effect of the cognitive load of the concurrent processing task does not interact with items' lexicality and frequency (Camos et al., 2019; Labaronne, Jarjat, et al., 2023) and does not modulate the benefit of semantic cues (Loaiza & Camos, 2018), suggesting no reliance on LTM. Consistently, M.R. Johnson and colleagues' study (2007) showed stimuli-specific activations in corresponding perceptual areas when refreshing unfamiliar faces or scenes, suggesting that refreshing is available for (at least some) unfamiliar items.

In the present experiment, we found a disadvantage of using refreshing rather than verbal rehearsal in short-term recalls, and this effect seemed similar for both words and pseudowords. However at long-term, refreshing benefitted the delayed recall of words, but results for pseudowords were inconclusive due to a floor effect.

The time-frequency analyses revealed a similar memory load effect on frontal-midline theta power for both maintenance instructions with pseudowords. Similarly, no differential effect of instructions on occipito-parietal alpha power was found for pseudowords. Thus, it appears that contrary to the distinction we observed with words, maintenance of pseudowords with the two maintenance instructions led to similar oscillatory activity in both frontal theta and posterior alpha.

Together, these results indicate that the distinction between verbal rehearsal and refreshing is less clear for pseudowords than it is for words. Given the absence of effect on oscillatory patterns, one possibility is that participants were unable to comply with the refreshing instruction for pseudowords and always relied on verbal rehearsal, leading to similar oscillatory patterns between the two instructions. However, we note that the manipulation of instructions still affected differently the short-term memory performance of pseudowords and modulated the memory load effect on the ERPs of the concurrent processing

task similarly for both words and pseudowords, which does not support a strictly similar maintenance with the two instructions. Thus, another hypothesis is that participants did maintain pseudowords differently with the refreshing than with the verbal rehearsal instructions, but not the same way they refreshed words, and that we could not capture this difference in our EEG analyses. For instance, we proposed earlier that it is possible that a visual representation of the pseudoword is needed with both verbal rehearsal and refreshing to maintain the spelling of the item. Therefore, while we cannot confidently conclude that pseudowords cannot be refreshed, it seems at least that the instruction to refresh is implemented differently than for words.

This difference may be in line with views that hypothesize a strong involvement of LTM in WM tasks. For instance, it has been suggested previously that WM recall relies on LTM retrieval when rehearsal is prevented by a concurrent mathematical task during the retention delay (Rose et al., 2014). In this kind of tasks, activations are observed in semantic retrieval areas such as left ventrolateral prefrontal cortex and anterior temporal lobes during the encoding and retention phases, that predict later recall (Rose et al., 2015). However, Rose and colleagues' study (2014) shows that LTM involvement is more important in the hard mathematical condition compared to the easy mathematical condition, and previous evidence pointed that the depth of processing of the items affected WM recall only in surprise WM recall tests, when participants supposedly did not engage in active maintenance (Rose & Craik, 2012). Thus, these results suggest that LTM contributes to WM recall mainly when active maintenance is prevented. In the present study, given that instructions emphasized that participants were expected to actively maintain the items, and that the concurrent processing task used left ample free time to maintain (2000-ms of free time after a 700-ms processing item), it is unlikely that a LTM retrieval strategy solely accounts for the results observed under the refreshing instructions, as already noted in a previous behavioral study investigating

refreshing of pseudowords (Labaronne, Jarjat, et al., 2023). Refreshing as a LTM retrieval practice, as proposed by the covert retrieval model (McCabe, 2008), may be compatible with our results. Our results show a better long-term recall for words, particularly in trials with six words, which allow for more LTM retrieval practice, than in trials with two words. However, previous studies found that refreshing does not always promote episodic LTM, even when using familiar words (Labaronne, Jarjat, et al., 2023; Loaiza et al., 2023), and that attentional focus after attention-switching in a double-cue paradigm does not interact with or promote LTM (Mao Chao et al., 2023). Thus, the difference between words and pseudowords results in the present study is probably not tied to direct episodic LTM retrievals during WM recalls or maintenance delays. Yet, whether refreshing and episodic LTM retrieval differ is still unclear, and future studies should address this question more directly.

However, Rose and colleagues (2012) examined the effect of stimulus novelty in WM tasks by investigating the case of patient HC, a developmental amnesic with preserved semantic memory. They found that HC's WM performance when maintaining a single item was preserved for familiar faces and words, but was impaired for unfamiliar faces, low-frequency words, and pseudowords. Their results suggest that an intact hippocampus is necessary to maintain even a single novel item, leading the authors to propose that the hippocampus may be critically important for WM tasks that needs bindings of features for novel items. Therefore, it may instead be that the main difference between words and pseudowords in the present study lies not in the kind of maintenance engaged, but rather in the kind of representation established, as we will discuss further later.

### **Does refreshing benefit long-term memory?**

Previous literature proposed that refreshing promotes LTM, based on the observation that cognitive load affects delayed recall on top of short-term recall (Camos & Portrat, 2015; Jarjat et al., 2018, 2020). However, this point is debated because other studies have not



consistently replicated the delayed cognitive load effect (Labaronne, Jarjat, et al., 2023; Loaiza et al., 2023), the long-term benefit of refreshing opportunities (Abadie & Camos, 2018), or argued that the long-term effect of WM is due to other mechanisms such as elaboration (Bartsch et al., 2018). Here, we proposed to bring new insight into this question by using a more direct manipulation of refreshing through direct instructions.

We observed a benefit of using refreshing on delayed recall, supporting the view that refreshing promotes LTM (Camos & Portrat, 2015; Jarjat et al., 2018, 2020). However, we found this benefit only for words. This result is consistent with the observation that the delayed advantage of items studied in complex span compared to simple span was found with words but not pseudowords (Loaiza et al., 2015). As we observed stronger recruitment of visual areas when refreshing words (compared to verbal rehearsal) but it did not differ between rehearsing and refreshing pseudowords, it may suggest that the long-term effect of refreshing depends on the ability to recruit visual areas during maintenance for these items. However, this proposition alone is unable to explain how a cognitive load effect on delayed recall is sometimes observed with words (Camos & Portrat, 2015) and sometimes not, even after it affected short-term recall (Labaronne, Jarjat, et al., 2023; Loaiza et al., 2023).

These results are difficult to reconcile with the current view of refreshing. In the next section, we will raise and try to address two questions about the nature of refreshing. First, if participants indeed used mental imagery to maintain words, is it still considered refreshing? Secondly, how could we explain that the effects of refreshing on memory may vary with the type of item maintained?

### **The nature of refreshing**

The most intuitive interpretation of our results is that the refreshing instruction led participants to form and maintain mental images of the content of the words (i.e., mental image of a referent), a strategy known to improve long-term recall (e.g., Bartsch et al., 2018;

Oliver et al., 2016), which was not possible with pseudowords. Given that the mental imagery strategy is commonly considered to be in the realm of elaboration, it seems essential to address the question of its involvement under “refreshing” instructions. Elaboration is defined as the enrichment of the memory representation of an item by linking it to the preexisting LTM content, which has been shown to improve episodic LTM ( Craik & Tulving, 1975; Gallo et al., 2008). Bartsch and colleagues (2018) conducted a study aiming at disentangling the effects of refreshing and elaboration on short- and long-term memory. The two strategies were manipulated through instructions, refreshing being described as thinking of the corresponding word, while elaboration required forming a vivid mental image of the word. They concluded that refreshing only preserves short-term memory, while elaboration has no effect on short-term recall but benefits LTM. Thus, one could hypothesize that our results reflect the use of elaboration instead of refreshing. However, we would argue against the sole effect of elaboration in our experiment. Elaboration has been shown to not benefit short-term memory performance (Bartsch et al., 2018; Bartsch & Oberauer, 2021), which would lead us to expect more drastic memory loss at short-term than what was observed under the refreshing instruction if no other maintenance mechanism supports it. We instead propose that a combination of elaboration and refreshing concepts may better explain our results. Elaboration refers to the enrichment of a memory representation, focusing on a modification of the representation itself. On the other hand, the refreshing’s central concept is that it is the use of attention to reactivate a memory representation, with no assumption on the kind of representation reactivated as refreshing is a domain-general mechanism (Barrouillet et al., 2007; Camos et al., 2018; Langerock et al., 2018; Souza et al., 2018). Therefore, it may be more appropriate to view elaboration and refreshing not as opposed, but rather as complementary: after the initial elaboration, the enriched representation is repeatedly refreshed to preserve its accessibility at short-term, also possibly promoting long-term

retention at the same time. Following this view, our results could indicate that mental images were formed for words and then refreshed throughout the maintenance period, as suggested by the recruitment of visual areas, which benefited LTM for these items. As discussed earlier, it could even be argued that words could be maintained in a single representation, such as a visual scene, as suggested by the absence of effect of memory load on frontal-midline theta power when refreshing words. Conversely, pseudowords could not be converted to mental images, and thus needed to rely on refreshing another kind of representation, without any benefit for LTM. Therefore, we propose that the use of mental imagery does not argue against the use of refreshing for maintenance. Instead, it may be that refreshing was used on both words and pseudowords, but the effect on memory varied with the kind of memoranda because of differences in the nature of the refreshed representations. It should be noted that we did not control for words concreteness and imageability in the present experiment, and thus the use of mental imagery is still speculative. Future studies will be necessary to confirm whether our pattern of results reflects this strategy.

Although it is not formally stated in the definition, in the behavioral literature refreshing seems to be taken as a self-sufficient construct. To rephrase, when looking at the way refreshing is investigated, the kind of representation maintained sometimes seems to be considered as a part of the refreshing mechanism itself. In other views, refreshing is rather conceived as a minimal executive function (Raye et al., 2007) or a kind of reflective attention (M. R. Johnson & Johnson, 2009). Coherently in the neuroimaging literature, a two-phase model for refreshing has been proposed, according to which frontal regions initiate the reactivation of perceptual areas responsible for the perception of the maintained stimuli (M. R. Johnson et al., 2007, 2015). Expanding on this latter view, refreshing could be conceived as the initiation and coordination of the reactivation of relevant areas, but not the reactivation itself. The reactivated areas (and thus the type of representation refreshed) would depend on

the nature of the memoranda, encoding processes, and following alterations of the representation such as elaboration, that modulate the observed impact of refreshing on WM and LTM. According to this proposition, refreshing could be used on mental images, pseudowords, other kinds of representations, or even enrichments of the representation such as inter-items relations. In the same line, Marcia Johnson (1992) proposed that LTM mainly depends on organizational processes such as inter-item relations, that are strengthened by later reactivation<sup>4</sup> and thus benefit long-term recall. If this hypothesis is true, we should be able to find a common component of refreshing followed by item-specific activations when refreshing different types of representations (e.g., M. K. Johnson et al., 2005; van Ede et al., 2017). For instance, van Ede and colleagues (2017) investigated the neurophysiological bases of WM using visual or tactile sequences. They identified three modality-independent components (frontal theta synchronization, frontoparietal gamma synchronization, and sustained parietal event-related fields) that predicted the modality-specific suppression of alpha and beta oscillations in sensory areas relevant to the type of memoranda maintained (i.e., left and right primary somatosensory areas for tactile sequences, and left and right early visual areas for visual sequences). Thus, our results may be better understood by considering that refreshing effects on memory do not depend only on the use of refreshing, but also on what is refreshed. However, additional studies would be needed to further develop this hypothesis.

## Conclusion

The present study shows that attentional refreshing and verbal rehearsal could successfully be distinguished using neural oscillations. Additionally, using direct refreshing

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<sup>4</sup> The MEM framework (M. K. Johnson, 1992) distinguishes between refreshing and reactivating. The author proposed that after noting and discovering relations between items, these compound representations are strengthened by reactivating and retrieving, but not by refreshing and rehearsing.

instructions and EEG oscillatory activity measurements allowed us to bring new insight into refreshing functioning, specifically around its benefit on long-term memory and the ability to refresh novel memoranda. While many questions on refreshing functioning are still open, the study of brain oscillations could prove very interesting in future investigation of refreshing, and more generally to disentangle different maintenance strategies.

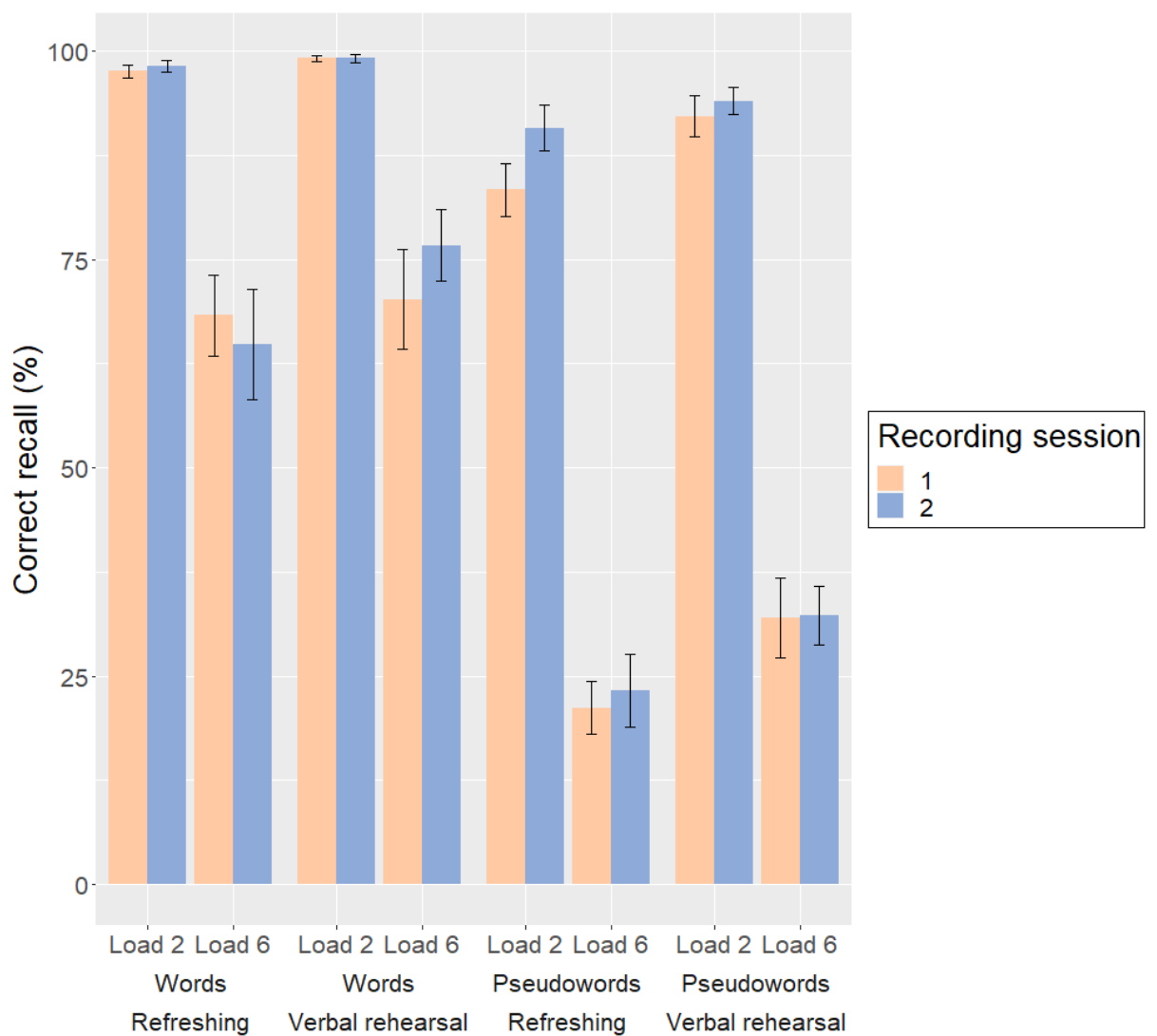
## **Appendix 1**

### **Methodological controls**

To ensure that participants complied with the given maintenance instructions and that there was no carryover effect between instructions (i.e., between the two recording sessions), we conducted a supplementary analysis on the effect of instructions order. An ANOVA was conducted on immediate serial recall, with instructions order, memory load, maintenance instructions, and item type as predictors. Overall, this analysis revealed no effect of instructions order (Figure 10). Results showed no significant effect of instructions order,  $F(1, 28) < 0.00, p > .10$ . Instructions order did not interact with item type,  $F(1, 28) = 2.78, p > .10$ , with memory load,  $F(1, 28) = 0.58, p > .10$ , or with instructions,  $F(1, 28) = 1.53, p > .10$ .

Secondly, we analyzed the effect of the number of syllables of the to-be-remembered items on recall. It is known that longer words have an increased maintenance demand, especially when using articulatory rehearsal (e.g., Baddeley et al., 1975). We conducted two independent ANOVAs on serial immediate and delayed recall, with number of syllables, memory load, maintenance instructions, and item type as predictors. There was an item type  $\times$  number of syllables interaction on immediate recall,  $F(1, 29) = 14.79, p = .005, \eta^2_G = .001$ , showing that the effect of the number of syllables was significant for pseudowords,  $t(29) = 4.64, p < .001$ , but not for words,  $t(29) = 1.50, p = .14$ . The same interaction was observed on delayed recall,  $F(1, 29) = 7.06, p = .013, \eta^2_G = .002$ , again indicating a significant effect for pseudowords,  $t(29) = 4.89, p < .001$ , but not for words,

$t(29) = 0.48, p > .10$ . It should be noted that the conditions in which the one and two-syllables long items were presented was counterbalanced between the four versions of the experiment, except between the conditions of memory load which had a different total number of items presented. These analyses thus show that longer verbal items impaired more the recall of pseudowords than words, but the effect of the number of syllables was not confounded with any of the other manipulated factors.



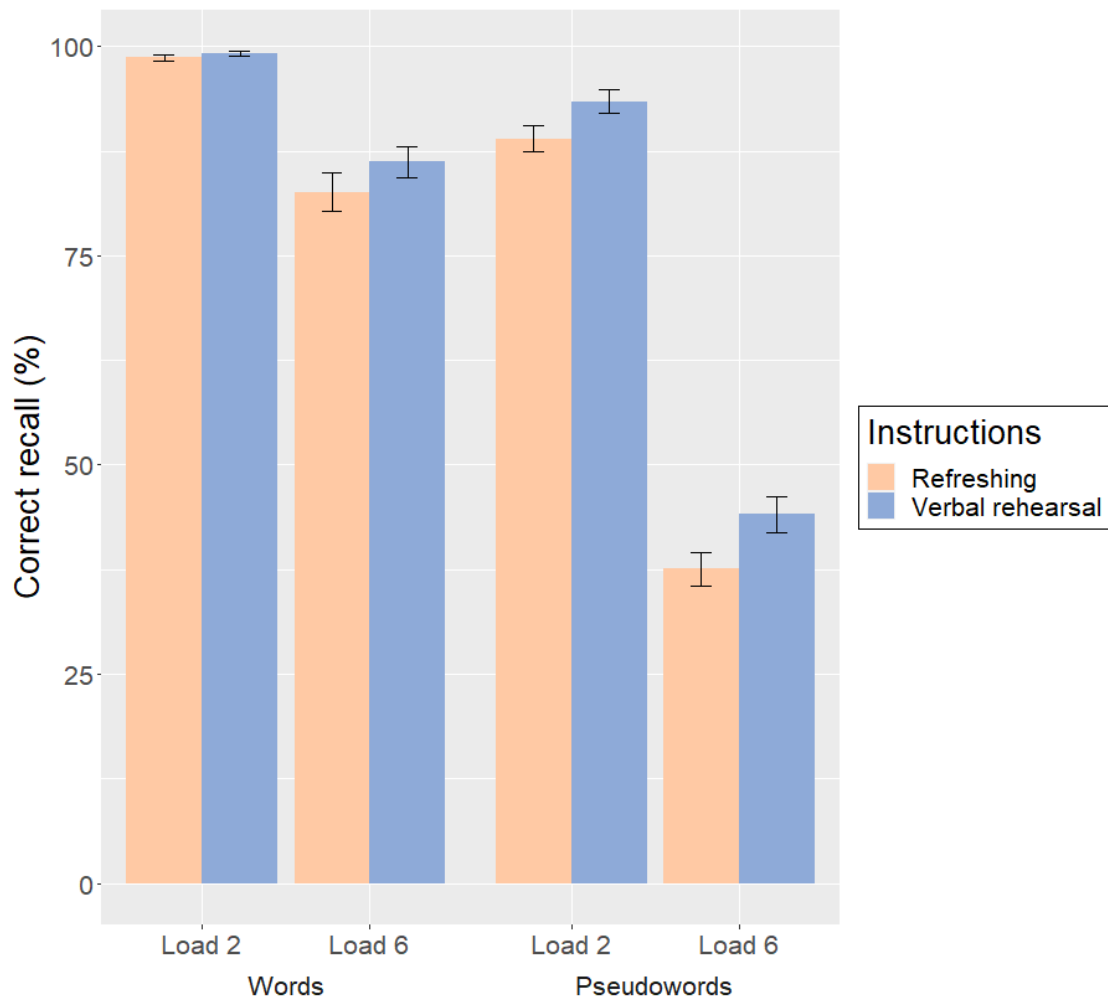
**Figure 10.** Percentage of correct serial recall at immediate recall by order of recording session, memory load, item type, and maintenance instruction. Error bars represent the standard error.

## Appendix 2

### Free recall analysis

We computed a free recall scoring, which is similar to serial immediate scoring but does not take into account the serial position of the recalled items. Thus, a correct free recall encompasses items correctly recalled at their correct serial position, items recalled but at a wrong serial position, and items recalled in the “free recall” box of the response sheet.

As a supplementary analysis, an ANOVA was conducted on the percentage of correct free recall, using the memory load, maintenance instructions, and item type as predictors. Besides an overall increase in performance, the effects were the same as those observed in immediate serial recall (see Figure 11). We observed a main effect of maintenance instructions with better performance when using verbal rehearsal ( $M = 72.92\%$ ;  $SD = 8.67$ ) rather than refreshing ( $M = 68.49\%$ ;  $SD = 8.63$ ),  $F(1, 29) = 13.25$ ,  $p = .001$ ,  $\eta^2_G = .042$ , and a significant instructions  $\times$  item type interaction,  $F(1, 29) = 9.45$ ,  $p = .005$ ,  $\eta^2_G = .009$ . As for immediate serial recall, this interaction stems from the ceiling effect when recalling two words. We also found a main effect of item type with better recall for words ( $M = 88.01\%$ ;  $SD = 7.73$ ) than for pseudowords ( $M = 53.41\%$ ;  $SD = 9.43$ ),  $F(1, 29) = 537.56$ ,  $p < .001$ ,  $\eta^2_G = .670$ . Additionally, recall was better under low ( $M = 95.05\%$ ;  $SD = 3.97$ ) than high ( $M = 65.60\%$ ;  $SD = 9.44$ ) memory load,  $F(1, 29) = 676.47$ ,  $p < .001$ ,  $\eta^2_G = .764$ . The memory load effect was significant for both words ( $t(29) = 8.39$ ,  $p < .001$ ) and pseudowords ( $t(29) = 39.88$ ,  $p < .001$ ), but larger for pseudowords (+50.38) than words (+14.53) as revealed by the item type  $\times$  memory load interaction ( $F(1, 29) = 433.43$ ,  $p < .001$ ,  $\eta^2_G = .497$ ). Again, this interaction probably reflects the ceiling effect when in the conditions with two words.



**Figure 11.** Percentage of correct free recall at immediate recall by memory load, item type, and maintenance instruction. Error bars represent the standard error.

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### **Data Availability Statement**

Material, data, and analysis scripts are available on the Open Science Framework at the following link: <https://doi.org/10.17605/osf.io/JBKX7>.

### **Author Contributions**

Maximilien Labaronne: Conceptualization; Data Curation; Formal Analysis; Investigation; Methodology; Project Administration; Software; Visualization; Writing – Original Draft Preparation; Writing – Review & Editing. Anne Caclin: Methodology; Writing – Review & Editing. Gaën Plancher: Conceptualization; Funding Acquisition; Methodology; Supervision; Writing – Review & Editing.