

Sensory modality affects the spatiotemporal dynamics of alpha and theta oscillations associated with prospective memory

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ARTICLE INFO

Keywords:

Alpha
theta
Time-frequency
Prospective memory
Sensory modality

ABSTRACT

Background: The maintenance of an intention in memory (Prospective Memory, PM) while performing a task is associated with a cost in terms of both performance (longer response times and lower accuracy) and neurophysiological modulations, which extent depends on several features of the stimuli.

Aim: This study explores the neural patterns associated with PM in different sensory modalities, to identify differences depending on this variable and discuss their functional meaning.

Method: Data were collected using a High-Density EEG during a baseline and a PM condition, proposed in a visual and an auditory version. Theta and alpha oscillations were compared between the two conditions within each modality using a cluster-based permutation approach.

Results: PM conditions were associated with clusters of decreased alpha and theta activity in both modalities. However, different spatiotemporal dynamics were elicited as a function of sensory modality: alpha decreases displayed an overlapping onset between modalities, but different durations, lasting longer in the auditory modality. Conversely, the clusters of decreased theta activity presented similar durations between modalities, but different temporal and spatial onsets, appearing at different moments over the respective sensory areas.

Conclusions: The similar spatiotemporal properties of alpha suppression between modalities indicate that such oscillations may represent a supramodal, top-down process, presumably reflecting the external direction of attention to successfully detect the prospective cue (strategic monitoring). In theta, the clusters showed more modality-specific differences, which temporal and spatial properties correspond to the ones necessary to perform the ongoing task, suggesting a shift in resource allocation in favor of the PM task.

1. Introduction

Every day, people move through an environment full of stimuli, while simultaneously maintaining information in memory to retrieve them at the most convenient time. For instance, they may form the intention to discuss a specific topic with a colleague once they encounter them, or to add a specific ingredient to the meal they are cooking after exactly 10 min. The ability to remember to perform an intended action at some point in the future is defined as prospective memory, or PM (McDaniel and Einstein, 2007).

Remembering to perform a delayed intention requires multiple steps. First, the intention must be encoded in memory and associated with a stimulus (a specific moment or event labeled as *PM cue*) at the

occurrence of which the intention will be retrieved. Subsequently, the intention must be maintained in memory while simultaneously monitoring the environment for the presentation of the PM cue. Finally, when the PM cue occurs it must be recognized, and the associated intention recalled from memory (Kliegel et al., 2000). Therefore, PM processing requires to balance resources between memory processes (to maintain the intention in memory) and attentional ones (to detect the PM cue in the environment). Typically, other activities (i.e., *ongoing tasks*) are attended during the retention period. How is the balance between maintenance, monitoring, and processing of the ongoing task reached? Several studies have demonstrated that the successful retrieval of an intention can be carried out both automatically, relying on the spontaneous recognition of the PM cue at its presentation (a process labeled as

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<https://doi.org/10.1016/j.ijpsycho.2023.112284>

Received 3 August 2023; Received in revised form 10 November 2023; Accepted 15 December 2023

Available online 16 December 2023

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spontaneous retrieval), or through a set of intentional top-down monitoring processes, defined as strategic monitoring (Einstein et al., 2005; McDaniel and Einstein, 2000). Moreover, during strategic monitoring, attention can be directed outward—to search for the PM cue in the environment—or inward, directed to the intentions maintained in memory to refresh and retrieve them (Cona et al., 2015; Guynn, 2003, 2007). The typical paradigm to investigate PM consists of two conditions, one in which the ongoing task is presented alone (baseline condition), and one in which the same task is proposed together with a prospective instruction (PM condition) (Einstein and McDaniel, 1990). The engagement in strategic monitoring processes in the latter block is typically evidenced by longer reaction times (RTs) and lower accuracy in the ongoing task, a phenomenon defined as *PM cost* (Anderson et al., 2019; Marsh et al., 2003; Smith, 2003).

Concerning the neural bases of PM, several neuroimaging studies have shown that a broad set of regions subserve this function. Namely, the addition of a PM task was associated with enhanced activity in the anterior prefrontal cortex, the cingulate cortex, the superior parietal lobule, and the dorsal and ventral portions of the frontoparietal network (Burgess et al., 2001, 2011; Gonneaud et al., 2014). Furthermore, these regions showed to be selectively enrolled depending on the selected mechanism (spontaneous retrieval vs. strategic monitoring) and on the perceptual features of the PM task (Cona et al., 2015, 2016; McDaniel et al., 2013; Simons et al., 2006).

The vast majority of the studies on the neural correlates of PM were conducted using functional magnetic resonance (fMRI), a neuroimaging technique with an excellent spatial resolution (in the order of the millimeter) but low temporal precision. Considering that cognitive processes occur at very fast temporal scales, the implementation of neurophysiological techniques such as electroencephalography (EEG) and magnetoencephalography (MEG), which collect data with an excellent temporal resolution (in the order of milliseconds), can contribute to the understanding of the fast dynamics underlying PM mechanisms. Furthermore, data collected with these instruments allow the classification of neural oscillations in different bands depending on their frequency, each associated in the literature with different functional roles. The theta (5–7 Hz) and alpha (8–12 Hz) frequency bands, in particular, are associated with balancing internal and external attention (Kam et al., 2019; Klimesch, 1999; Magosso et al., 2021). Specifically, increased theta activity has been associated with an increased focus on internal processes, such as memory integration and semantic processing (Backus et al., 2016; Fuentemilla et al., 2014). Alpha waves, instead, have been consistently found to decrease when attention was directed outward (external monitoring) and to increase for tasks requiring internal attention (Benedek et al., 2014; Klimesch, 2012; Pfurtscheller et al., 1996).

In the first study investigating PM using MEG (Martin et al., 2007), the authors found that the maintenance of the intention was related to increased theta activity over hippocampal regions and decreased alpha activity over parietal ones. Cona et al. (2020) broaden the investigation on the neural correlates of PM processing with the implementation of a paradigm composed of PM conditions enhancing either the monitoring (external attention) or maintenance (internal attention) requests of the PM task. Significant differences were found between conditions, as the focus on internal contents produced increased theta activity over medial temporal regions, whereas the enhancement of external monitoring was reflected in patterns of decreased theta and alpha activity over posterior regions. In a recent study, we applied the same paradigm by Cona et al. (2017, 2020) to compare the PM costs associated with the maintenance- and monitoring-enhancing conditions between different sensory modalities (Vicentin et al., 2022). To do so, we developed a visual and an auditory version of the same PM paradigm.

The rationale beyond the involvement of the variable “sensory modality” in the investigation of PM was based on several reasons. First, several perceptual features of the stimuli (salience, focality) already showed to influence PM processing (Scolaro et al., 2014; Scullin et al.,

2010; Smith et al., 2007). Second, considering that in everyday activities acoustic stimuli can be associated with an intention as likely as visual ones, the involvement of multiple sensory modalities could increase the ecological validity of the previous results on PM. Lastly, the involvement of multiple sensory modalities in the study of cognitive processes can contribute to their understanding (Klein and Stolz, 2015), accumulating evidence on either the presence of modality-specific effects or on their supramodal nature. Despite research rarely collect and compare data from different sensory modalities (Hutmacher, 2019), the few studies that did so reported significant differences that brought to interesting interpretations on the considered cognitive domains. For instance, Cohen et al. (2009) reported that participants were significantly worse in the recognition of previously presented sounds compared to images, whereas Amon and Bertenthal (2018) found the performance in a Working Memory task to be better (but slower) in the auditory modality. The sensory modality in which stimuli were proposed was found to also affect the neural oscillations associated with the underlying cognitive processes. Specifically, Krause et al. (2006) compared the power elicited in different frequency bands (theta, alpha, and beta) between an auditory and a visual version of a Lexical Decision Task (LDT). Auditory stimuli elicited greater power decreases in the alpha and beta band, together with an enhanced lexicality effect (difference between word and non-word processing), whereas visual strings of letters were associated with greater power increases in the theta band. On the other hand, Lopez-Zunini et al. (2020), investigated the differences between a visual and an auditory LDT from the event-related potential (ERP) perspective, identifying different time windows in which the lexicality effect was greater in the two modalities (~300 ms for visual stimuli, ~700 ms for auditory ones).

Regarding PM, the presence of an effect associated with sensory modality was reported at the behavioral level in our previous study (Vicentin et al., 2022). In detail, a greater PM cost was found when the task was proposed in the auditory modality, but selectively when the properties of the intention enhanced attentional requests, thus increasing strategic monitoring. This first evidence of an interaction between sensory modality and focus of attention on PM processing increased our interest in the investigation the neural bases subserving strategic monitoring in the two modalities.

Starting from our previous behavioral findings, the present research aims to shed light on the spatiotemporal dynamics of the neural oscillations associated with PM in different sensory modalities. To do so, we collected EEG data during a classical PM paradigm (baseline + PM condition) proposed twice, once with stimuli displayed in the visual modality and once with auditory stimuli. The analysis focused on the theta and alpha frequency bands, due to their functional meaning (association with memory and attentional processes, respectively) comparing the activity found in the PM condition with the respective baseline block within each modality. In line with the methodology applied by Lopez-Zunini et al. (2020), we did not compare directly neural oscillations between the auditory and the visual versions of the experimental blocks, because of the perceptual differences between visually and auditory presented strings of letters (auditory stimuli were presented sequentially, syllable-by-syllable, whereas visual ones were displayed globally from the beginning). Instead, the analysis focused on the differences at the neurophysiological level associated with the addition of a prospective request, comparing the baseline and the PM conditions within each sensory modality. The comparison between the baseline and the PM conditions is a well-established method in the literature on PM to highlight the effects associated with intention maintenance, and the elicitation of different patterns of neural oscillations between modalities may contribute to highlight the presence of differences in PM processing related to the variable sensory modality.

Considering the previous neurophysiological findings on the neural oscillations associated with PM (Cona et al., 2020; Martin et al., 2007) we would expect the elicitation of consistent decreased alpha activity over posterior regions in the PM condition, a phenomenon associated

with strategic monitoring. Critically, however, since PM research was always conducted in the visual modality, a first aim of this study was the identification of the corresponding spatiotemporal pattern in the auditory modality. Considering the top-down, stimulus-independent nature of strategic monitoring, we would expect similar patterns of posterior alpha reduction to be elicited also in the auditory modality. Yet, considering the results of Krause et al. (2006) comparing visual and auditory versions of the LDT, power decreases in the alpha band are also expected to be greater in the auditory modality. Regarding the theta band, in the visual modality clusters of reduced activity are expected over occipito-temporal regions, in line with the ones elicited in Cona et al. (2020). Critically, however, the interpretation of these results was less straightforward than the ones on the alpha band. Thus, a second aim of this research is to gain additional information on the functional meaning of this phenomenon to increase its interpretability. The detection of differences in the temporal or spatial properties of the clusters in the two modalities would account for the bottom-up, modality-specific nature of the process underlying theta decreases. Considering the association of theta activity with both lexical and memory processes, we would expect the cluster of decreased activity in the auditory modality to present a delayed onset and a topography involving more anterior (central and temporal) regions compared to the visual modality (Lopez-Zunini et al., 2020; Kawasaki et al., 2014).

2. Methods

2.1. Participants

A statistical power analysis was performed using G*Power software (Faul et al., 2007) to calculate the minimum sample size for the statistical analysis, that was identified in 36 subjects (effect size $f = 0.25$, power $b = 0.95$). Behavioral and EEG data were collected from a total of 40 participants, but two acquisitions presented some technical issues (in one case the amplifier shut off, and in the other behavioral data were not saved), leading to a final population of 38 participants (11 males; mean age = 25 years, range 18–32). All participants possessed normal or corrected-to-normal visual acuity and their hearing was tested during the practice phase. The study was approved by the local Ethics Committee of the University of Padua and followed the guidelines of the Helsinki Declaration, and every participant signed a written informed consent before the beginning of the experiment.

2.2. Experimental procedure

The experiment was programmed using E-Prime 3.0 software (Psychology Software Tools, 2021) and consisted of four blocks. Specifically, the experiment included an auditory and a visual version of a PM paradigm, both composed of a baseline block—where the ongoing task was administered alone—and a PM condition, composed of the same ongoing task and a PM task. In the baseline conditions, participants were asked to perform a Lexical Decision Task (LDT), i.e., to judge the lexicality of each presented string of letters (if they correspond to a word or not). In the PM conditions, the LDT was administered with the addition of a PM instruction: participants had to remember to press a specific key as soon as they detected a specific syllable within the string of letters (the syllable <<TA>>). Nonfocal, nonsalient PM tasks such as the one proposed here are known in literature to require and stimulate external monitoring (Rummel and McDaniel, 2019; Scullin et al., 2010), and were found to be affected by sensory modality (Vicentin et al., 2022). Baseline blocks were composed of 100 ongoing trials, whereas PM conditions consisted of 100 ongoing trials plus 8 PM cues (i.e., stimuli presenting the syllable “TA”; frequency: 7.4 %). To make their detection more difficult, at least 10 ongoing trials occurred between each pair of PM cues. Before the baseline block, a practice phase (10 LDT trials) was presented in each modality, to ensure that participants understood the instructions and familiarized with the task.

Regardless of the sensory modality, each trial was structured in the same way: First, a fixation cross appeared in the center of the screen for a pseudorandom duration (1250 ± 250 ms). Subsequently, the string of letters was presented, lasting until a response was given or for a maximum of 2000 ms. Thus, a blank screen was presented for 1000 ms, serving as the inter-stimulus interval (see Fig. 1). Visual and auditory stimuli were selected from a previously created dataset (Vicentin et al., 2022) and were balanced for length, frequency, and initial letter across conditions. In the auditory version of the experiment, the stimuli consisted of audio recordings of an experimenter reading the strings of letters aloud. Each recording had a duration of 1000 ms and was delivered at ~ 70 dBA (at the ear level) from two speakers positioned on the sides of the screen. Visual stimuli consisted of white strings of letters presented in the center of a gray screen, in Arial font. Within each version of the paradigm, the baseline was always presented before the PM task. Instead, the order of presentation of the auditory and the visual versions of the paradigms was counterbalanced across participants. Likewise, the buttons associated with the responses to the LDT were counterbalanced.

2.3. Recording procedure

Neurophysiological data were acquired using a 256-channels High-Density EEG system (EGI, Electrical Geodesic Inc) with a sampling rate of 1000 Hz and referencing each electrode to their average. Scalp circumference was measured to select the EEG cap that fitted better the head of the participant. Furthermore, the central point of the head (Cz) was identified and marked with a washable pencil to increase the precision of the montage. Once the preparation was completed, participants were placed in the electrically shielded room in which the amplifier and the acquisition screen were placed, and the impedances of each electrode were checked and reduced to be lower than 50 k Ω .

2.4. EEG preprocessing

Data analyses were performed using Brainstorm (Tadel et al., 2011). First, continuous data were downsampled to 250 Hz and filtered in the 0.5–40 Hz band. Power Spectrum Density and visual inspection (performed independently by three different researchers) were applied to detect electrical artifacts and electrodes differing for >50 μ V from the mean. Independent component analysis algorithms (ICA Infomax) were applied to the continuous recording to detect and remove ocular, cardiac, muscular, and electrical artifacts. Trigger timing of the auditory stimuli was adjusted to account for the delay in the presentation of the sound, measured in 40 ms.

Subsequently, recordings were cut in epochs of 3 s from 500 ms before the stimulus presentation to 2500 ms after. The length was chosen to account for the edge effect in the time-frequency analysis. Only trials containing correct responses to the ongoing task (LDT) were considered for the analysis. Trials containing PM cues were ignored because of their scarce number (8 out of 108 in each PM block), and because of the impossibility to compare them with the baseline condition. Selected epochs were further visually inspected by three researchers to exclude the ones still presenting traces of artifacts in the time window of interest [0–2000 ms]. Finally, removed electrodes were interpolated to increase the spatial reliability of the analyses (maximum distance: 2 cm).

2.5. Time-frequency analysis

Time-Frequency analyses were run on the preprocessed epochs to investigate how the activity was distributed in time and in the frequencies of interest (theta, 5–7 Hz; alpha, 8–12 Hz). Specifically, each epoch was convolved using the Morlet wavelets to estimate the spectral power in the frequency range of alpha and theta, separately. Wavelet cycles were set at three cycles at the lowest possible frequency (1 Hz) to

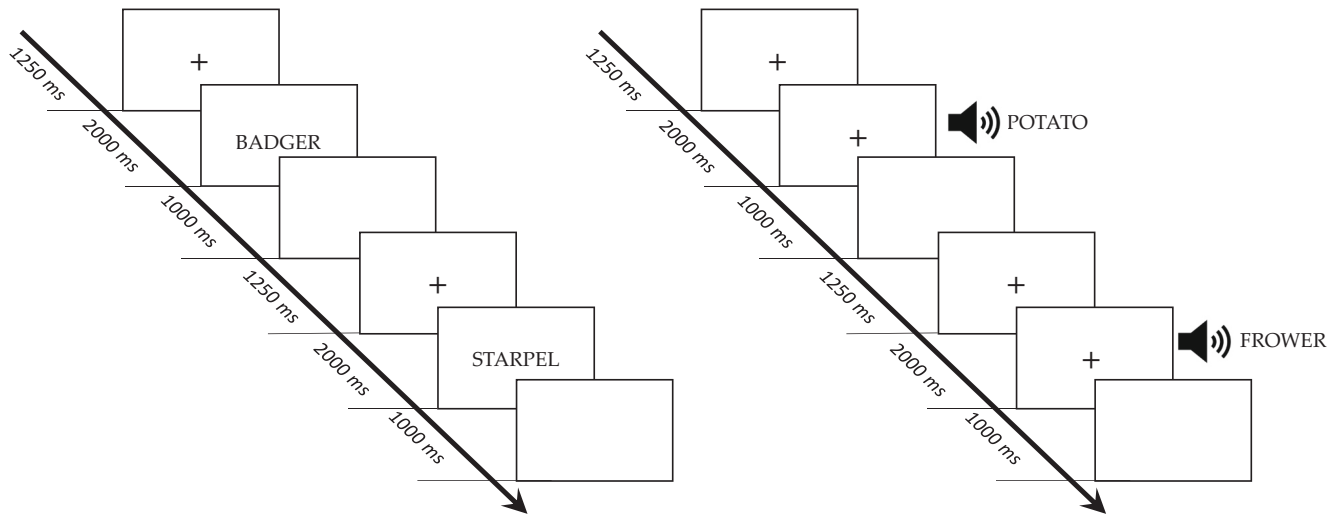


Fig. 1. General structure of the experimental paradigm, in the visual (left) and the auditory version (right). In the baseline conditions, participants were asked to perform the Lexical Decision Task (LDT). In the PM conditions, participants were asked to keep performing the LDT, but also to remember to press a different button everytime the syllable < TA > (written in the visual version and spoken in the auditory) was presented.

increase the resolution of the obtained Time-Frequency maps. Magnitude values were extracted for each sensor and time point and then averaged between epochs within conditions. Baseline correction was applied on the resulting Time-Frequency maps using Event-Related Synchronization/ Desynchronization (ERS/ERD) calculated on the $[-500; -200]$ ms prestimulus time windows.

2.6. Statistical analysis

Behavioral data were analyzed using JASP, an open-source software for statistical analysis (Version 0.16.3; 2022). Repeated-measures Analysis of Variance (rm-ANOVA) was applied to investigate the presence of effects of sensory modality and/or PM request on performance in the ongoing task, separately for response times (RTs) and accuracy. Each rmANOVA had a 2 (modality: auditory vs. visual) \times 2 (Condition: baseline vs. PM condition) within-subjects design. Post-hoc analyses were run to investigate the effect of each factor separately, applying the Bonferroni correction to compensate for multiple comparisons. Regarding neurophysiological data, the Time-Frequency maps were compared using a cluster-based permutation approach (Groppe et al., 2011; Maris and Oostenveld, 2007). This method allows to compare the activity collected by each sensor at each time point, grouping the significant differences in temporally and spatially resolved clusters. To account for multiple comparisons, results were corrected using the permutation method (number of permutations: 1000). The cluster-based permutation was applied on the time window of interest $[0; 2000]$ ms, comparing the activity in the PM task and the baseline condition, separately for sensory modality (visual, auditory) and frequency of interest (alpha, theta) for a total of four comparisons. Images displaying the comparison between sensory modalities, focusing on relevant time points, are presented in the Time-Frequency Results section (3.2), whereas video clips presenting the whole spatiotemporal dynamics in both modalities and frequency bands can be found as supplementary materials.

Finally, a correlation analysis was run to investigate the relationship between performance and neural oscillations associated with intention maintenance. To investigate the link between the behavioral PM cost (both in terms of Response Times and Accuracy) and power decreases, we applied the Pearson correlation method, as in Maurer et al. (2015). To do so, power decreases were calculated as the difference between the Power Spectrum Density (PSD) values extracted from the baseline and the PM conditions. In detail, PSD were calculated in each epoch in the

time window of interest $[0; 2000]$ ms using the Welch method (Window length: 3.00 s; Overlap ratio: 50 %) and focusing on the electrodes belonging to the clusters of significantly different power between conditions (104 electrodes in the alpha band, 96 for theta). Subsequently, PSD values were averaged within each condition, and the difference in power was computed as the difference between the log-transformed power values in the baseline and the PM conditions, separately for each electrode. Finally, the obtained results were averaged among all the considered electrodes, obtaining a single value for each modality and frequency band representing the average power difference between the two conditions.

3. Results

3.1. Behavioral results

3.1.1. Reaction times

A robust effect of sensory modality was found on RTs $[F(1, 37) = 349.631; p < .001; \eta_p^2 = 0.904]$, as in the auditory modality participants were on average 400 ms slower than in the visual. An effect of the variable “condition” was also present $[F(1, 37) = 360.113; p < .001; \eta_p^2 = 0.907]$, with RTs being on average 200 ms slower in the PM conditions compared to the baseline ones. The interaction between the two factors was significant $[F(1, 37) = 360.113; p = .008; \eta_p^2 = 0.177]$, reflecting a greater PM cost (i.e., increased RTs between PM block and baseline block) in the auditory modality than in the visual (228 ms vs. 179 ms; $p = .014$, see Fig. 2). Post-hoc analysis confirmed that each condition differed significantly from all the others (auditory PM task = 1383 ms, baseline = 1155; visual PM task = 961 ms, baseline = 782; $p_{\text{bonf}} < 0.001$).

3.1.2. Accuracy

The number of correct responses was affected by both sensory modality $[F(1, 37) = 8.219; p = .007; \eta_p^2 = 0.182]$ and condition $[F(1, 37) = 34.336; p < .001; \eta_p^2 = 0.481]$. The effect of their interaction was also significant $[F(1, 37) = 40.570; p < .001; \eta_p^2 = 0.523]$, indicating that the effect of the PM task was different in the two modalities. More specifically, the post-hoc analysis revealed that performance was significantly lower in the auditory version of the PM task (88.9 %) compared to all the other conditions ($p_{\text{bonf}} < 0.001$), which instead did not differ from each other. Namely, as can be seen in Fig. 2, participants in the auditory PM block were ~ 8 % less accurate than in the auditory baseline (96.8 %),

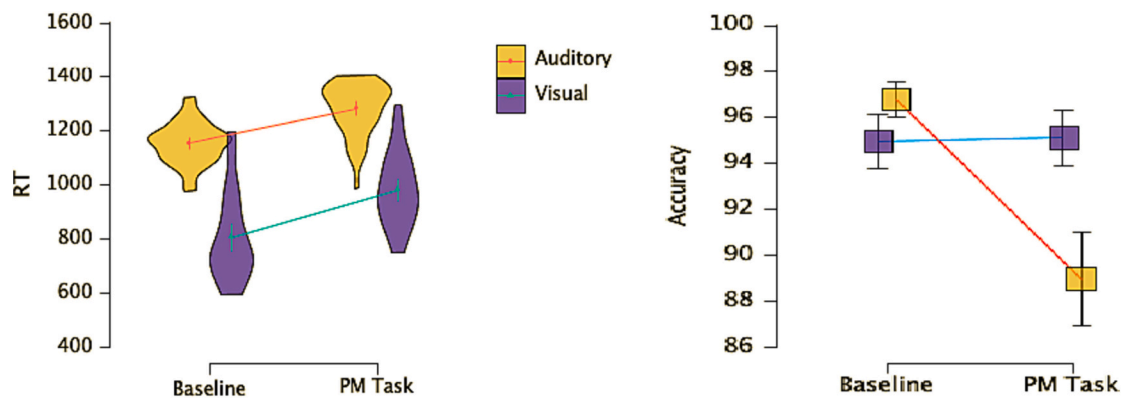


Fig. 2. Mean Reaction Times (left panel) and Accuracy (right panel) in the visual (blue) and the auditory (yellow) modalities. Error Bars Represent Standard Errors. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and ~ 6 % less accurate than in the same condition in the visual modality (95.1 %). In the visual version, performance did not differ between the baseline (95.0 %) and the PM conditions, suggesting that the PM cost was present selectively in the auditory modality.

3.2. Time-frequency results

The comparisons between the PM blocks and the baseline conditions

were carried out by using the cluster-based permutation approach (Groppe et al., 2011; Maris and Oostenveld, 2007). This method allowed us to highlight the significant differences between conditions as clusters of electrodes (spatially or temporally adjacent), showing similar patterns of increased/decreased EEG activity. In the following paragraphs, we refer to the differences between conditions in terms of the properties of these clusters, namely their Cluster Size (CS, the number of sensors presenting a significant difference between conditions), Cluster Mass

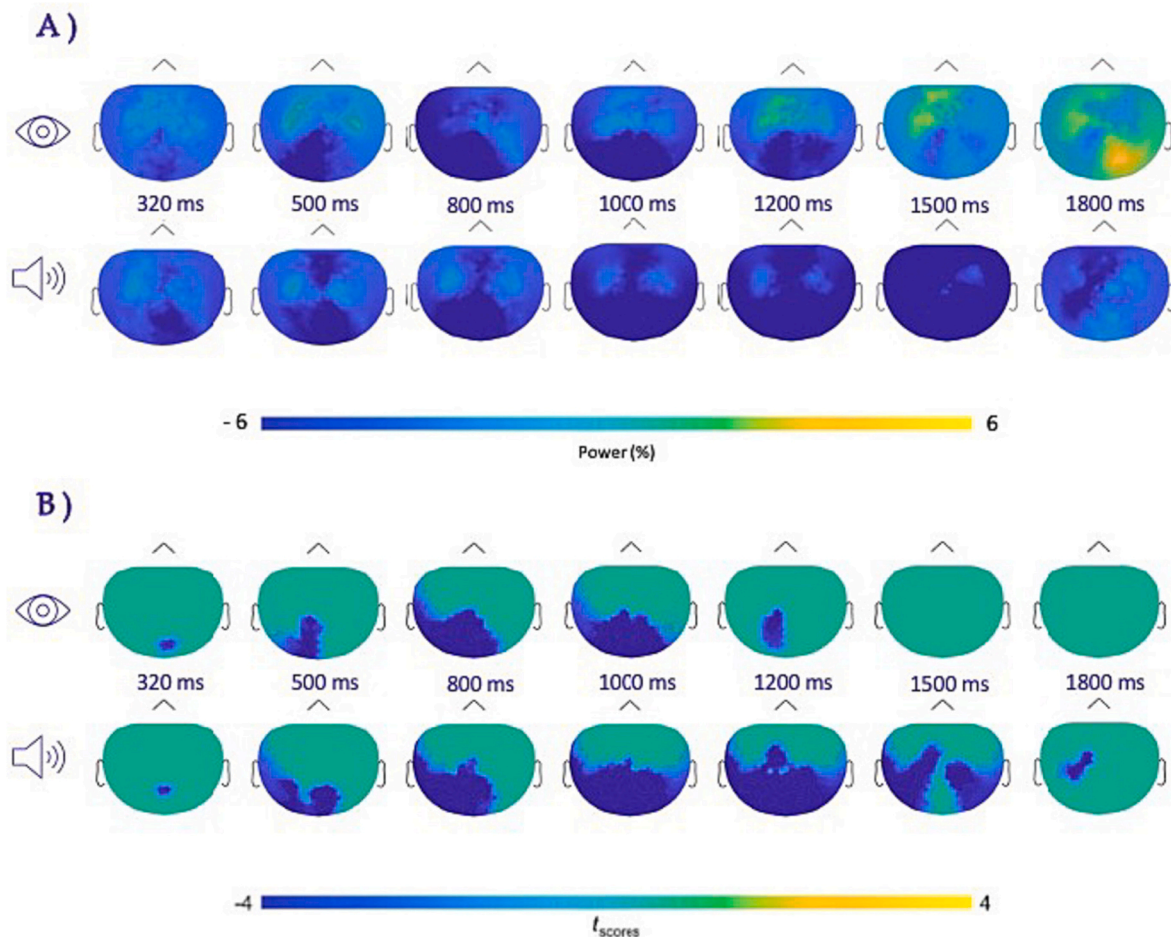


Fig. 3. A) Spatial and temporal patterns of power differences between the baseline and the PM condition in the Alpha band, in the visual (upper line) and auditory (bottom) modality. B) Clusters of electrodes presenting statistically significant decreases in power (in blue) between the baseline and the PM conditions, in the visual (upper line) and auditory (bottom) modality. The displayed time points were selected on the basis of the results, to highlight the main differences between sensory modalities. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(CM, the sum of the t-values of these sensors), Largest Spatial Extent (LSE, the moment in which the cluster reach its maximum size), and the level of significance of the cluster (p.value). The time courses of the clusters in the two modalities are reported in the supplementary materials section, separately for the alpha (Fig. S1) and theta (Fig. S2) frequency bands.

3.2.1. Alpha

Comparing the two PM conditions (auditory and visual) with the respective baselines, similar clusters of decreased alpha power were found in both modalities (Fig. 3). In particular, both clusters appeared over the same occipital regions around 320 ms after the stimulus presentation. In the visual modality the cluster (CS = 15,976; CM = -44,764; LSE: 1152 ms; $p = .012$) was first detected over occipital and left parietal regions (320–600 ms), and then over left temporal and right posterior sites (600–1000 ms). The cluster remained stable over posterior regions until ~1200 ms, when it started to shrink to the left parietal regions, to disappear at 1350 ms. In the auditory modality, the cluster (CS = 31,853; CM = -97,509; LSE: 1276 ms; $p = .002$) extended first to the left inferotemporal regions (400–600 ms), then to left parietal ones (600–800 ms). Between 800 and 1300 ms, it spreads over all posterior regions bilaterally and over the left centro-frontal ones. Subsequently, the cluster started to decrease, focusing on bilateral temporal and parietal regions, and over left central sites (1300–1700 ms). At ~1750 ms,

decreased activity was present only over central regions of the left hemisphere, to disappear at 1850 ms.

3.2.2. Theta

The addition of the PM task was associated with patterns of decreased theta activity in both modalities (Fig. 4A). In detail, the cluster in the visual modality (CS = 6998; CM = -17,245; LSE: 512 ms; $p = .034$), started at 240 ms over right occipital regions. Decreased power then englobed bilateral occipital and parietal sites (240–500 ms). Afterward, the cluster began to shrink, first over all the right posterior regions (500–650 ms), then to the parietal one (650–750 ms). In the auditory modality, the cluster of decreased activity (CS = 9741; CM = -27,338; LSE: 852 ms; $p = .0240$) appeared over left temporal regions at 650 ms (Fig. 4B, bottom line), thus spreading with a left to right evolution, involving all posterior regions first (650–800 ms), then right temporal ones (800–1000 ms). Finally, it begins to shrink with the opposite pattern (right to left), focusing over the left temporo-parietal regions it originated from, until disappearing at ~1150 ms.

3.3. Correlation analysis

Two correlation analyses were addressed to explore the relationships between performance and power decreases in the theta and alpha frequency bands: one focusing on the differences between conditions in the

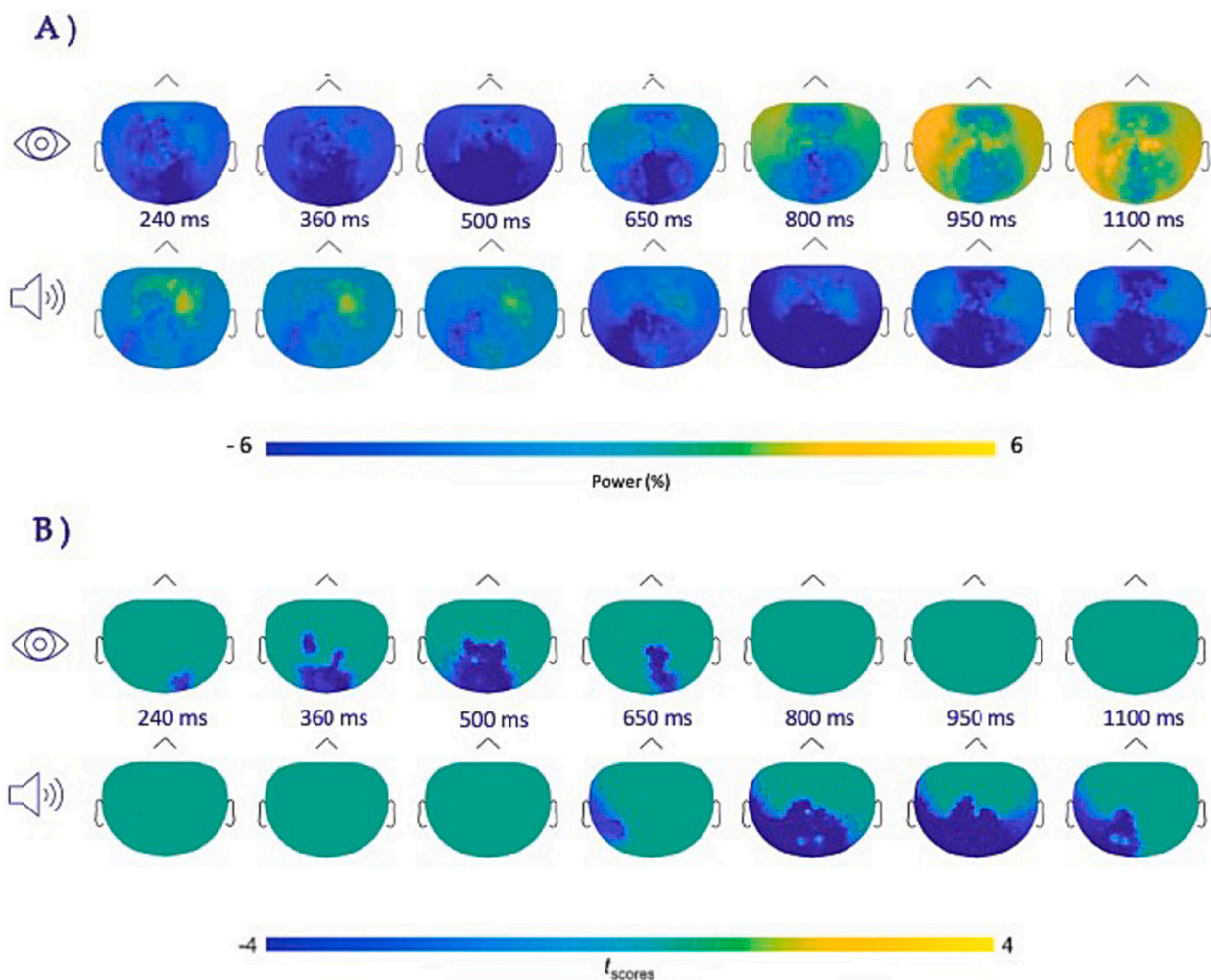


Fig. 4. A) Spatial and temporal patterns of power differences between the baseline and the PM condition in the Theta band, in the visual (upper line) and auditory (bottom) modality. B) Clusters of electrodes presenting statistically significant decreases in power (in blue) between the baseline and the PM conditions, in the visual (upper line) and auditory (bottom) modality. The displayed time points were selected on the basis of the results, to highlight the main differences between sensory modalities. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

auditory modality (Fig. 5.A), and the other focusing on the visual version of the paradigm (Fig. 5.B).

In the auditory modality, the difference in power between conditions showed a strong correlation between frequency bands ($r = 0.713$, $p < .001$). Additionally, a strong correlation between PM costs in terms of RTs and in terms of accuracy was found ($r = 0.427$, $p = .007$). Critically, however, no correlation between power decreases and behavioral performance was found. The same was true for the visual modality, in which only theta and alpha decreases displayed a significant association ($r = 0.327$, $p = .045$).

4. Discussion

In the present study we investigated alpha and theta oscillations associated with prospective memory (PM) processing in an auditory and a visual version of a PM paradigm, to compare patterns of neural activity associated with the addition of a prospective task in different sensory modalities. To do so, we analyzed differences in EEG dynamics between the PM and the baseline conditions within each modality, using a cluster-based permutation approach. The differences and similarities in the spatiotemporal dynamics of the clusters in the two modalities are discussed to highlight their commonalities and modality-dependent properties. This approach aims to determine if the sensory modality in which stimuli are presented may have an impact on the neurocognitive processes underlying PM, deepening the understanding of the brain mechanisms engaged during prospective remembering and their modifications in response to the perceptual features of the involved stimuli.

In general, the addition of a PM task to an ongoing activity was reflected in patterns of decreased alpha and theta activity elicited during the ongoing task, consistently between sensory modalities. Nevertheless, the topographical and temporal properties of these clusters resulted to differ between modalities. In the visual modality, the clusters extended mostly over bilateral posterior regions (occipital and parietal sites), whereas in the auditory clusters were more widespread, involving also temporal and centro-frontal regions, and tended to be more long-lasting and lateralized to the left hemisphere. Hence, in the auditory modality the addition of the PM task seems to require the enrollment of a broader set of regions to be processed. Considering the greater PM cost in the auditory version of the PM task, which replicates our previous findings (Vicentin et al., 2022), this pattern may reflect the necessity to rely on additional neural bases to perform the PM task in the auditory modality.

Regarding the results in the alpha band, the association between the increased monitoring requests and the decreased alpha power found for

the PM conditions in both modalities is in line with the functional role of this frequency band proposed by previous studies. Namely, oscillations in the alpha rhythms are considered a marker of attentional processes, and decreased activity in this frequency band has been associated with external monitoring (Benedek et al., 2014; Pfurtscheller et al., 1996; O'Connell et al., 2009). PM studies analyzing alpha activity consistently reported decreases in the 8–12 Hz rhythm during strategic monitoring processes, in particular for monitoring-enhancing PM tasks (Cona et al., 2020; Laera et al., 2021). The administration of a PM task with similar features in the present study produced results that closely parallel the ones of Cona et al. (2020) in the visual modality. Furthermore, the involvement of a second modality allowed us to collect additional evidence on the association between alpha decreases and top-down attentional processes. In detail, the clusters of decreased activity in the alpha band in the two modalities were found to have a common onset, but different evolutions in time. Specifically, both clusters started 320 ms after the stimulus presentation over occipital regions. The cluster in the visual version lasted for approximately 1000 ms, extending over bilateral posterior regions and left temporal ones. In the auditory modality, the cluster occurred over the same sites, but recruited additional regions such as the right temporal and the left fronto-central ones. Moreover, decreased alpha activity in this modality had a longer duration (~1500 ms). The overlapping temporal onset and the similarity of the spatial dynamics between the visual and the auditory clusters suggest that they may reflect a common—supramodal—cognitive process. It has been suggested that the absence of differences depending on sensory modality can be considered an index of the top-down nature of undergoing activity (Klein and Stolz, 2015; Ward, 1994; Wahn and König, 2017). Furthermore, consistent associations between alpha decreases and high-level memory processes have been found in the auditory modality (Erickson et al., 2019; Krause et al., 1996, 1999). In this light, the common onset of the clusters of decreased alpha activity in the two modalities supports the hypothesis that said clusters reflect top-down processes. Given the above-mentioned literature on the alpha band and the similar properties of the clusters collected in the two modalities, our findings in the alpha band may reflect a top-down process. In particular, the patterns of decreased alpha power could be interpreted as a marker of increased strategic monitoring, a mechanism that is thought to be top-down and stimulus-independent (Barban et al., 2014; Cona et al., 2015; McDaniel et al., 2015). The involvement of additional regions in the auditory modality, on the other hand, may be associated with the increased difficulty to perform the PM task in this modality, as corroborated by the behavioral results. Regarding its longer duration, it

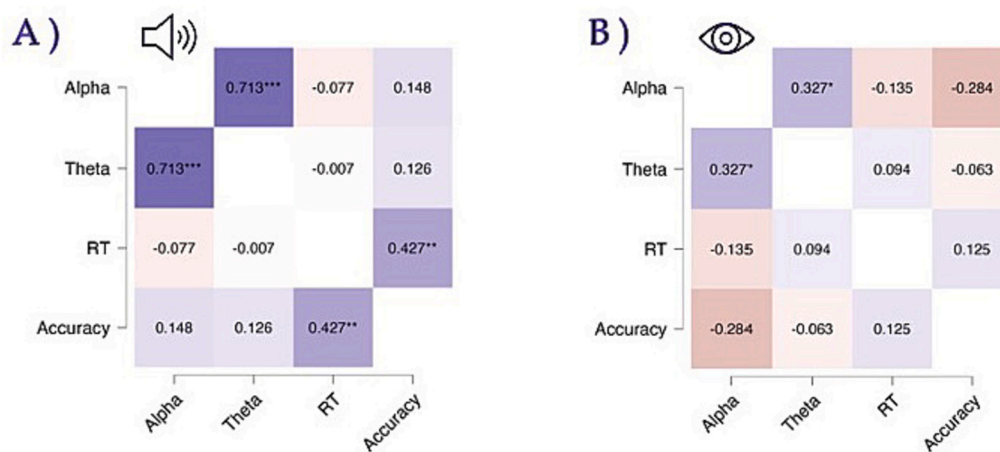


Fig. 5. Correlation analysis of differences between the baseline and the PM conditions, considering both the behavioral and the neurophysiological levels. A) On the left, correlations between power decreases (Alpha, Theta), response times (RT) and Accuracy in the Auditory modality. B) On the right, correlation between the same variables in the Visual modality.

*** $p < .001$, ** $p < .01$, * $p < .05$.

must be pointed out that acoustic strings of letters must be processed sequentially (syllable-by-syllable), requiring longer times to monitor each syllable and compare them with the PM cue. Visual strings of letters, instead, are displayed entirely from the first moment of the stimulus presentation and are therefore processed globally. In this light, the increased response times in the auditory modality can reflect perceptual differences between modalities (Krause et al., 2006).

In the theta band, on the other hand, clusters presented similar durations (~500 ms) across modalities, but different onsets and topographies. Specifically, in the visual modality the pattern of decreased activity started at 240 ms over occipital sites, spreading to all posterior regions before shrinking to the right parietal ones. In the auditory, the cluster occurred at 650 ms over the left temporal regions, extending over the bilateral posterior and the contralateral temporal sites before starting to shrink to the left posterior regions. Theta activity is known to play a pivotal role in memory processes and, in general, in processes oriented to internal contents (Backus et al., 2016; Fuentemilla et al., 2014). Therefore, decreased activity in this frequency band has been linked with lower attention toward internal contents (Kam et al., 2019; Magosso et al., 2021). Accordingly, in their study Cona et al. (2020) reported increased theta activity in the PM task enhancing maintenance load and decreased power in the condition enhancing external monitoring load. The authors interpreted these patterns as signatures of attention directed either to the internal contents or outward, for the detection of the PM cue. The patterns of reduced activity found in our study are consistent with this interpretation. The temporal and topographical properties of the clusters found in the two sensory modalities, however, allow us to speculate more on the interpretation of the functional meaning of theta decreases. In fact, a pivotal finding of this research is that the patterns of decreased theta power in the two modalities begin over the respective sensory regions (occipital in the visual, temporal in the auditory). Since such clusters represent the difference associated with the addition of a PM instruction, we expected them to be reflected over regions involved in PM-related processing, especially considering the monitoring-enhancing nature of the selected PM task. The onset of these clusters over sensory regions, instead, may suggest that more bottom-up mechanisms underlie these differences. Importantly, in the auditory modality the onset of the cluster corresponded to the moment in which the last syllable of the acoustic stimuli was presented. Therefore, the differences between conditions in this modality start to appear only once the stimulus was completely presented and started to be elaborated globally. The integration of the stimulus is a process more related to the ongoing task (LDT, asking to judge the lexicality of the presented string) than to the prospective request (asking to detect a specific syllable). Differences related to the PM task were expected to be elicited sooner, as in the case of the clusters in the alpha band. Furthermore, the offset of the clusters (744 ms in the visual, 1228 ms in the auditory) occurred closely to the average response times in the baseline condition (782 and 1155 ms, respectively). Given the above, it is possible that the decreased power in the theta band may reflect, rather than an increased involvement in the PM task, a “disengagement” from the ongoing one, namely a decreased allocation of cognitive resources to the ongoing task. This hypothesis is also driven by the fact that increased theta activity has been associated with lexical and semantic processing (Bastiaansen et al., 2005; Krause et al., 2006), and from the results of a study that investigated the LDT in the visual and the auditory modality, in which the authors found that the lexicality effect in the two modalities occurred in the same time windows in which our clusters appeared (Lopez-Zunini et al., 2020). Altogether, these findings may suggest that the decreased theta activity found in monitoring-enhancing PM tasks can reflect the lower involvement in the ongoing (lexical decision) task, a more bottom-up and stimulus-dependent process, rather than the increased involvement in the prospective one. Notably, the two interpretations are not mutually exclusive, as both reflect the re-allocation of resources occurring when the prospective task is added to the LDT. Additional research can be addressed to further define the functional

role of theta decreases, either involving different types of ongoing tasks or comparing different types of PM tasks across sensory modalities. The implementation of cross-modal PM paradigms, presenting visual PM cues embedded in auditory ongoing tasks and vice versa, would be a further step in the investigation of PM processing, getting closer and closer to real-life situations in which this complex mechanism takes place.

To investigate the relationship between behavioral and neurophysiological PM costs, we conducted a correlation analysis between theta and alpha power decreases and the differences in Response Times and Accuracy, separately for sensory modality. The analysis revealed a positive correlation between neural oscillations in the two frequency bands, meaning that greater alpha reductions were consistently paired with greater theta decreases, in both visual and auditory modalities. Instead, a significant association between behavioral PM costs was found selectively in the auditory modality. Namely, greater delays in Response Times were associated with increased number of errors in the PM condition compared to the baseline. The selective significance of this effect for acoustic stimuli may be related to the increased difficulty of the task, which increased the variability of the results. However, this analysis failed to detect any association between behavioral and neurophysiological differences between the PM and the baseline conditions.

This study had some limitations that must be considered. First, the time required to perform the ongoing task (LDT) differed between sensory modalities, since judging the lexicality of a string of letters requires more time in the auditory modality, where it must be processed syllable by syllable first, and then integrated. In the visual modality, instead, the immediate presentation of the whole string of letters allows the simultaneous processing of its lexicality (the ongoing task) and the search for a specific syllable (the PM task). The second limit consist in the fact that the PM task itself (the detection of a specific syllable) may have been more difficult in the auditory modality, since each syllable was presented only once and for a limited amount of time, whereas in the visual modality the whole string of letters was displayed globally for all the interval length (until response, or for 2000 ms max). Subsequently, PM processing may have occurred in different time windows in the two modalities. For these reasons, analyses focused on an indirect comparison of the neural correlates of intention maintenance in the two modalities, that previous studies had indicated as the most methodologically appropriate approach (Lopez-Zunini et al., 2020).

Despite the abovementioned limits, the decision to use the LDT as the ongoing task was motivated by the fact that linguistic stimuli can be considered one of the few cases in which the same concept can be equally associated with a visual and an auditory stimulus. Moreover, strings of letters (words in particular) represent naturalistic stimuli that are often encountered in our everyday life, both in their visual (written) and auditory (phonological) representations. Regarding the difficulty differences of the PM task in the two modalities, research on PM often investigates the effect of perceptual features that are known to modulate the difficulty of the PM task, such as saliency and focality (Einstein et al., 2005; Cona et al., 2016). The manipulation of these variables inherently leads to increased levels of difficulty, which are considered part of the feature itself (see Rummel and McDaniel, 2019). In our study, the hypothesis of increased difficulty of the PM task (syllable detection) in the auditory modality would fit with the observation of more sustained patterns of alpha decreases. Such patterns can be interpreted in line with the ATODI model and considered as markers of enhanced strategic monitoring (the same occurs with non-salient stimuli; Cona et al., 2015, 2020).

A third limit consists in the fact that participants performed the two versions of the PM paradigm (visual and auditory) consequently. Thus, together with the possible presence of practice and fatigue effects on the second version, it is also plausible that during the execution of the second baseline condition participants were already expecting to be presented with a second PM task. This problem may have been partially

compensated by the counterbalanced order in which the two versions were presented in, but some effect on the increased expectation may still have been present. Finally, regarding the analysis, the applied cluster-based permutation approach has been demonstrated to be a useful tool for exploratory studies, investigating new phenomena without a priori indications on their temporal and topographical patterns. However, the resulting significance of the cluster indicates only the general validity of the difference, not allowing to compare, for instance, the extent of the involvement of a particular region (Maris and Oostenveld, 2007; Sassenhagen and Draschkow, 2019). For this reason, no analysis on pre-specified brain regions were conducted in this study. However, given the differences in the time windows in which our processes of interest occurred in the two modalities, cluster-based permutation analyses represented the most appropriate approach for this first, explorative study on the neural oscillations associated with intention maintenance in different sensory modalities.

Altogether, the involvement of two different sensory modalities in the study of PM resulted in the opportunity to broaden the knowledge of this cognitive process by revealing new insights on the functional meaning of the neural oscillations associated with the maintenance of an intention. While alpha reductions confirmed their role as a marker of top-down, supramodal mechanisms such as strategic monitoring in both modalities, the temporal and spatial properties of the theta decreases seem to suggest their association with more stimulus-dependent processes.

5. Conclusions

The current study investigates for the first time the neural correlates of prospective memory in different sensory modalities. Theta and alpha oscillations showed to play a pivotal role in prospective memory processing in both sensory modalities, as clusters of decreased activity in these frequency bands were present in both versions of the paradigm. Alpha decreases presented similar onset and dynamics, thus suggesting its association with top-down, stimulus-independent processes such as strategic monitoring. The extent over more widespread regions and the longer duration of the cluster in the auditory modality, instead, may reflect an increased difficulty in the auditory version of the prospective task. Theta decreases, on the other hand, showed more modality-dependent patterns. The different onset and the similar duration (corresponding to the windows in which the lexicality effect occurs in the ongoing task) suggest that such differences may be associated with a decreased involvement in the ongoing activity, rather than with intention maintenance per se.

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ijpsycho.2023.112284>.

Declaration of competing interest

None.

Data availability

Data will be made available on request.

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