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Review

Electrophysiological markers of mind wandering: A systematic review

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A B S T R A C T

The ability to mentally wander away from the external environment is a remarkable feature of the human mind. Although recent years have witnessed a surge of interest in examining mind wandering using EEG, there is no comprehensive review that summarizes and accounts for the variable findings. Accordingly, we conducted a systematic review that synthesizes evidence from EEG studies that examined the electrophysiological measures of mind wandering. Our search yielded 42 studies that met eligibility criteria. The reviewed literature converges on a reduction in the amplitude of canonical ERP components (i.e., P1, N1 and P3) as the most reliable markers of mind wandering. Spectral findings were less robust, but point towards greater activity in lower frequency bands, (i.e., delta, theta, and alpha), as well as a decrease in beta band activity, during mind wandering compared to on-task states. The variability in these findings appears to be modulated by the task context. To integrate these findings, we propose an electrophysiological account of mind wandering that explains how the brain supports this inner experience. Conclusions drawn from this work will inform future endeavours in basic science to map out electrophysiological patterns underlying mind wandering and in translational science using EEG to predict the occurrence of this phenomenon.

1. Introduction

The human mind has a remarkable capacity to disconnect from the immediate environment and wander off to another time or place. Often characterized as thoughts minimally constrained by the ongoing task or external environment, this phenomenon of mind wandering can occupy a notable portion of our awake mental life. Sometimes they facilitate creative problem solving (Baird et al., 2012; Gable et al., 2019; Leszczynski et al., 2017) and planning for the future (Baird et al., 2011; Kvavilashvili and Rummel, 2020); other times, they disrupt task performance (Randall et al., 2014) and are linked to negative mood when thought content was negative (Poerio et al., 2013), and to clinical disorders such as depression and attention deficit/hyperactivity disorder (Bozhilova et al., 2018; Moukhtarian et al., 2020). Given their prevalence and strong associations with both adaptive and maladaptive functional outcomes, this class of cognition has received widespread interest in cognitive neuroscience. One common goal in particular involves identifying the neural correlates of mind wandering. To that end, electrophysiological recordings provide a direct measure of neuronal activity in the brain, and they afford the temporal resolution necessary for capturing fast-acting and time-sensitive neurophysiological processes during mind wandering. The relative low-cost and portable features of scalp EEG also enable applications in real-world settings, further enhancing its value in addressing both basic and translational science questions. In this review, we therefore synthesize evidence from scalp EEG studies that establish electrophysiological markers of mind wandering.

The study of mind wandering has historically relied on sampling an individual's in-the-moment experience multiple times throughout a task or the course of a day, commonly referred to as experience or thought sampling. Although this subjective report provides a direct measure of one's attentional focus and ongoing thought content, its reliability often gets called into question. Possibly as remnants of the behavioral era, the current zeitgeist continues to prioritize objective measures as optimal indicators of cognitive operations (Andrews-Hanna et al., 2018). Therefore, numerous studies have turned to behavioral and neural markers of mind wandering to corroborate subjective reports and make inferences about this covert cognitive state (Schooler and Schreiber, 2004; Smallwood and Schooler, 2015). Given the often internally oriented nature of mind wandering however, this phenomenon inherently lacks a universal, task-general behavioral marker similar to those that typically characterize externally oriented cognitive functions. Notably, changes in behavioral measures across task conditions do not readily inform which stage of information processing is involved during mind wandering. Electrophysiology addresses this issue: it has the capacity to uncover

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the *stages* of neural processes underlying covert attention states such as mind wandering as it unfolds over time.

Early scalp EEG studies examining the electrophysiological correlates of mind wandering have primarily utilized event-related potentials (ERP) components. This type of measure reflects neural activity that is time-locked to a sensory, cognitive, or motor event, characterized by their polarity (i.e., positive or negative going wave), amplitude, latency, and scalp distribution. Decades of research have established ERP components as useful biomarkers of cognitive operations, and indications of conditional or group differences (Handy, 2005; Luck, 2005). Given the precise temporal resolution of scalp EEG recordings, ERP components capture electrophysiological activity on the order of milliseconds and thus reveal different stages of information processing. In particular, they can be categorized into early components, primarily reflecting sensory level processing, and later components, mainly characterizing cognitive level processes. This enables the examination of which stage of stimulus-evoked processing is disrupted during mind wandering. In the context of mind wandering, the most commonly reported ERP components are the P1 in response to visual stimuli, indexing sensory level visual processing (Mangun & Hillyard, 1991), and the P3, indexing cognitive level processes such as context updating, resource allocation, and working memory load (Polich, 2007). As the functional interpretation of ERP components depends on the task and its stimuli, a variety of cognitive processes indexed by this measure have been examined in a diverse range of tasks employed to study mind wandering. Therefore, not only do ERP components serve as electrophysiological correlates of mind wandering, they also reveal the stage and type of processes that are impacted when the mind wanders.

In addition to ERP components, an increasing number of mind wandering studies have reported on spectral features of EEG data unfolding over time. This requires decomposition of the EEG signal into the time-frequency domain, in which signals are characterized by their frequency, amplitude, phase, and spatial distribution. Commonly categorized into canonical frequency bands (i.e., delta (1-4Hz), theta (4-8Hz), alpha (8-14Hz), beta (15-30Hz), and gamma (30-50Hz)) these signals are presumed to reflect oscillatory activity that have functionally distinct roles in human cognition (Ward, 2003). Given brain oscillations have been shown to facilitate communication within the brain (Fries, 2015; Varela et al., 2001), they not only serve as EEG markers of mind wandering but they can also inform potential neural mechanisms underlying this phenomenon. For example, the inhibitory role of alpha band has been purported to be the electrophysiological mechanism underlying selective attention (Foxe and Snyder, 2011; Jensen and Mazaheri, 2010). It has also been linked to visual attention and alertness (Klimesch et al., 1998; Sauseng et al., 2005). Likewise, ample evidence suggests that theta rhythms within and across brain regions subserve memory processes (Buzsáki, 2005), as well as attentional functions (Helfrich et la., 2018) and executive control functions (Cavanaugh & Frank, 2014). Building upon our current understanding of mechanistic roles of canonical frequency bands, EEG studies examining spectral features may uncover how they facilitate mind wandering.

In this review, we systematically evaluate evidence of electrophysiological markers of mind wandering in healthy adults. Despite the increasing interest in examining this phenomenon using EEG, there has been no comprehensive review thus far that summarizes and accounts for the variable findings in the field. To bridge the gap, this systematic review synthesizes studies reporting scalp EEG measures of mind wandering. Although numerous definitions of mind wandering exist, we focused on studies that adopted the most common conceptualizations of mind wandering: task-unrelated thought and stimulus-independent thought (Smallwood & Schooler, 2015). Our review of this growing body of literature will inform future endeavours in basic science to reveal electrophysiological mechanisms underlying mind wandering and in translational science to use EEG to predict the occurrence of this ubiquitous phenomenon.

2. Methods

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2009). The review protocol was created using the International Prospective Register of Systematic Reviews (PROSPERO) template and preregistered on Open Science Framework (https://osf.io/t492p/).

2.1. *Search Strategy*

To identify relevant studies on the EEG markers of mind wandering in healthy adults, we performed a comprehensive search using the following electronic databases: PsycINFO (OVID), Medline (PubMed), Scopus (Academic Search Complete), Web of Science Core Collection (Web of Science), IEEE Xplore Digital Library (IEEE Xplore), as well as ProQuest (for grey literature involving materials published outside of traditional publication channels such as preprints) between June 4th and 5th 2021. Only empirical articles written in English were considered, and no restrictions were applied on publication dates. Search terms were derived from the two core concepts in our review, mind wandering and EEG, and were restricted to the Title, Keywords, and Abstract sections in our search. Mind wandering terms included “mind wandering”, “task-unrelated thought”, “stimulus-independent thought”, “off-task state”, “spontaneous thought”, and “internal attention”. These were searched in conjunction with EEG terms, which included “EEG”, “electroencephalogram”, “event-related potentials” or “ERP”, “event-related spectral perturbation” or “ERSP”, “frequency power”, “oscillatory activity”, “delta”, “theta”, “alpha”, “beta”, and “gamma”. Search syntax and strategies were tailored to each search engine to ensure all search terms and their variations were considered. To ensure literature saturation, we also reviewed the reference section of all included articles as well as related major systematic reviews or meta-analyses.

2.2. *Selection Criteria*

Our inclusion criteria consisted of empirical studies 1) involving scalp EEG recordings obtained from healthy adults aged 18-65; 2) reporting scalp EEG measures associated with mind wandering; 3) reporting descriptive statistics of EEG measures and corresponding statistical analyses; and 4) using online, retrospective, or questionnaire-based self-report measures of mind wandering. These criteria were implemented to ensure that scalp EEG measures were obtained, and such data were statistically analyzed allowing for inferences to be made about mind wandering. We only considered studies that used self-report measures of mind wandering, as they provide a direct assessment of one’s attentional state. This includes experience sampling or online measures, in which one reports when they catch themselves mind wandering (i.e., self-caught) or reports their attentional state as prompted by the experimenter occasionally throughout the task (i.e., probe-caught); retrospective measures, which involves a subjective report of one’s overall attention during a task upon task completion; and trait questionnaires, which requires individuals to report their trait level propensity for mind wandering. Within the experience sampling approach, the main difference between self-caught and probe-caught measures is that the former involves a heightened sense of meta-awareness (Smallwood & Schooler, 2006; 2015). In contrast to experience sampling measures which capture mind wandering in the moment, the retrospective self-report approach requires one to reflect upon how often they mind wandered during a task upon task completion, and the trait questionnaire approach assesses overall tendencies to mind wander in everyday life. These subjective self-report measures avoid the need for researchers to make inferences about participants’ attentional states based on their behaviour. Further, studies involving clinical populations were included only if they reported statistical analyses on mind wandering measures for a healthy control group.

The following exclusion criteria were also implemented: 1) resting state with no self-report measure of mind wandering; 2) mind wandering measure based on inferences (e.g., behavioral measures); 3) simultaneous recordings of EEG and other neuroimaging measures if EEG measures were not independently reported; 4) multivariate analyses (e.g., machine learning) in the absence of statistical analyses of univariate measures, or 5) reviews, meta-analyses, opinion pieces, and case studies. We implemented a two-stage screening process. At stage one, two authors (T.R. and Y.P.) independently screened the titles, abstracts, and keywords according to the above selection criteria in Covidence, an online platform designed to manage systematic reviews. In cases of conflict between the two authors with respect to inclusion versus exclusion, a third author (J.W.Y.K.) made a final decision upon discussion with the other two authors. At stage two, T.R. and Y. P. screened full-text articles that were considered eligible from stage one.

2.3. Data Extraction

For each study, the following information was extracted: 1) study information (authors, title, location, publication year); 2) sample characteristics (age, gender/sex, eligibility criteria) and final sample size (included in analysis); 3) task description and duration; 4) mind wandering: definition (task-unrelated/off-task thought, stimulus-independent thought/internal attention), type of measures (experience sampling, retrospective, questionnaire), and details of measures; 5) EEG: electrodes number and layout, preprocessing information, type of measures (e.g., ERPs, frequency band activity) and their associated metrics (e.g., amplitude, latency), time-window and scalp/source location; and 6) statistical values relevant to the mind wandering effect on EEG measures (e.g., *F* values, *p* values, confidence intervals, Bayesian probabilities). In order to provide a cogent synthesis, we will summarize the results as a function of the EEG measures used in the studies (i.e., ERPs and spectral features).

To assess the quality of included studies, we adapted questions from two existing quality assessment tools and guidelines (i.e., Keil et al., 2014; Kmet et al., 2004). Since we are not aware of standardized criteria for the quality assessment of electrophysiological studies, we combined two separate resources that enabled us to evaluate the general study design and EEG methodological approaches. Specifically, the Standard Quality Assessment Criteria for Evaluating Primary Research Papers from a Variety of Fields (Kmet et al., 2004) was designed as a standardized set of criteria to assess the quality of primary research studies whereas the Publications Guidelines and Recommendations for Studies Using Electroencephalography and Magnetoencephalography (Keil et al., 2014) provides a set of publishing guidelines for M/EEG studies. Accordingly, the methodological rigour of the experimental design and EEG data acquisition and analysis were evaluated in the following areas: selection bias, study design, EEG artifact handling and appropriate preprocessing, definition of EEG measures (e.g., type of metric, spatial and temporal specificity), and completeness of reported information. The complete list of criteria is reported in Supplementary Table 1. Each criterion was assigned a quality score of 0 to 2 (0 = *weak quality/information not reported*, 1 = *moderate quality/partially reported*, and 2 = *strong quality/details reported* as they pertain to each criterion). These scores were averaged to create a global score assigned to each study. The results of this assessment are reported in Supplementary Materials.

3. Results

3.1. Search Results

Fig. 1 presents the screening and selection procedures based on the PRISMA guidelines. The initial search yielded 840 studies, 474 of which were duplicates and therefore removed. The remaining 366 papers went through initial and full-text screening, of which 324 were excluded. No additional papers were identified through reviewing references of eligible papers and recent reviews. Therefore, a final set of 42 articles published between 2000 and June of 2021 fulfilled the selection criteria and were included in the systematic review. These articles are summarized in Table 1 for ERP measures and Table 2 for spectral measures. Additional demographic information as well as timing information about the ERP and spectral measures are reported in Supplementary Tables 2 and 3 respectively.

Among the included papers, the predominant measure of mind wandering was the experience sampling approach ($n = 37$; with $n = 32$ using probe-caught and $n = 5$ using self-caught), followed by the retrospective self-report approach ($n = 5$). No studies used the trait questionnaire approach that assesses trait level mind wandering and its relationship to EEG markers. Supplementary Table 4 presents a summary of task and experience sampling parameters implemented in studies that adopted the experience sampling approach. The majority of the included papers reported on event-related potentials (ERPs; $n = 26$) and frequency band activity ($n = 23$), with the remaining papers examining microstates ($n = 1$) and fractal decomposition ($n = 1$). The sum of the reported number of studies per EEG measure category exceeds the total number of included studies ($N = 42$) because some studies reported both ERPs and frequency band activity. Given that the location, timing, and frequency of activity (in the case of spectral markers) all contribute to the interpretation of EEG measures, we highlight these characteristics in our summary and discussion of the studies.[1] Notably, the task context – particularly whether task stimuli required external versus internal attention – appears to play an important role in the direction of effects on EEG spectral activity, likely because this determines whether one is mind wandering away from external task stimuli or internal sensations such as breaths. Therefore, we summarize and discuss the spectral results separately for the studies using externally versus internally oriented tasks. Fig. 2 illustrates the proportion of these studies that showed effects of mind wandering on ERP and spectral measures. While Fig. 2 prioritizes showcasing the direction of effects, an illustration of our results that highlight the robustness of the findings is found in Supplementary Figure 2. Supplementary Table 5 presents a description of commonly implemented tasks as well as examined canonical ERP and spectral measures in the included papers in this review.

3.2. ERP Correlates of Mind Wandering

In this section, we report the summary of ERP correlates as a function of canonical ERP components separated into early and late stages of processing. Across the 26 ERP publications, many of which examined more than one ERP component, P1 was the most commonly reported sensory level ERP component (11 papers involving 15 tasks) and P3 was the most commonly reported cognitive level ERP component (19 papers involving 24 tasks).

3.2.1. Mind wandering effect on early ERP components

P1. Given that most studies reviewed here implemented tasks in the visual modality, they often examined the P1 measured across midline occipital sites to index sensory level processing of visual stimuli. All 11 studies that reported on the occipital P1 used visual stimuli in their tasks. Seven out of these 11 studies reported a decrease in P1 amplitude

[1] In the three that studies that included multiple tasks or experiments (two tasks: Bozhilova et al., 2021; Jin et al., 2019; one main experiment E1 plus two follow-up control experiments E2/E3: (Kam et al., 2011), two reported contrasting results across tasks/experiments involving the same EEG measure (P1 in Bozhilova et al., 2021 and P3 in Kam et al., 2011). For the ease of reporting and discussing results from these studies in the text, we counted that study as showing a positive result as long as one of the tasks (Bozhilova et al., 2021) or the main experiment (Kam et al., 2011) reported a significant attentional difference in that EEG measure. Table 1 reports the results from all tasks and experiments in these studies.

Table 1
Summary of mind wandering (MW) studies examining event-related potentials (ERP) measures included in this review, presented by type of MW measure.

Reference	Final Sample Size	Task (modality)	MW Measure	EEG Measures[2]	Early ERPs[1]	Late ERPs[1]
Baird et al. (2014)	N=16	0-back task (visual)	Experience sampling (probe)	P1 (parieto-occipital)	P1 ↓	-
Baldwin et al. (2017)	N=9	Driving task (visual) + thought probe (auditory)	Experience sampling (probe)	N1 (Cz) P3a (Fz and Cz) *ERPs time-locked to thought probe tones	N1 n.s.	P3a ↓
Bozhilova et al. (2021)	N=18 (SAT) N=21 (N-back)[4]	Sustained attention task (SAT, visual); N-back task (visual)	Experience sampling (probe)	P1 (parieto-occipital) P3 (centro-parietal)	P1 ↓ (SAT, d=0.98; N-back did not survive FDR correction)	P3 n.s. (SAT & N-back)
Broadway et al. (2015)	N=22	Reading task (visual)	Experience sampling (probe)	P1, N1, P3, N4 (lateral parieto-occipital)	P1 n.s. N1 ↓	P3 n.s. N4 n.s.
Denkova et al. (2018)	N=28	SART[3] with face stimuli (visual)	Experience sampling (probe)	N170 (lateral parietal) P1 (parieto-occipital) P3 (parietal)	P1 n.s. N170 ↓ ($\eta_p^2 = 0.20$)	P3 n.s.
Jaswal et al. (2019)	N=20[4]	SART (visual)	Experience sampling (probe)	P3 (parieto-occipital) LPP (centro-parietal)	-	P3 ↓ ($\eta_p^2 = 0.11$) LPP n.s.
Jin et al. (2019)	N=18	SART (visual); visual search task (visual)	Experience sampling (probe)	P1, N1 (lateral parieto-occipital) P3 (parietal)	P1 ↓ (d = 0.36) N1 ↓ (d = 0.31)	P3 ↓ (d = 0.50)
Kam et al. (2011)	N=22 (E1) N=15 (E2) N=12 (E3)	E1: SART (visual) E2: SART (visual and auditory) E3: SART (visual, upper/lower visual fields)	Experience sampling (probe)	P1 (occipital) *time-locked to visual stimulus N1 (midline frontal to parietal) *time-locked to tone (E2 only) P3 (Cz & Pz) *time-locked to visual stimulus	P1 ↓ (E1, E2, E3 – upper visual field) N1 ↓ (E2)	P3 ↓ (E1) P3 n.s. (E2, E3)
Kam et al. (2012)	N=15	Time-estimation task (auditory), performance feedback (visual)	Experience sampling (probe)	P3 (Cz & Pz) fERN (FCz) **ERPs time-locked to visual performance feedback*	-	P3 ↓ fERN ↓ (d = 0.61)
Kam et al. (2013)	N=20	Passive oddball tones during reading (auditory)	Experience sampling (probe)	N1 (Fz & Cz) *N1 time-locked to tones	N1 ↓	-
Kam et al. (2014a)	N=12	SART (visual, left/right visual fields)	Experience sampling (probe)	P1 (lateral parieto-occipital; contralateral electrodes tested for left/right visual fields) P3 (parietal)	P1 ↓ (left visual field)	P3 n.s.
Kam et al. (2014b)	N=19	Affective categorization task (visual)	Experience sampling (probe)	Early positive wave (fronto-central) Late ascending slope (fronto-central) Late P3 (centro-parietal)	Early positive wave n.s.	Late ascending slope ↓ ($\eta_p^2 = 0.49$) Late P3 n.s.
Kam et al. (2015)	N=14[4]	SART (visual)	Experience sampling (probe)	P3 (midline frontal to parietal)	-	P3 n.s.
Kam et al. (2021)	N=39	Categorization task (visual)	Experience sampling (probe)	P3 (parietal)	-	P3 ↓
Macdonald et al. (2011)	N=11	RSVP detection task (visual)	Experience sampling (probe)	P3 (midline centro-parieto-occipital)	-	P3 ↓ ($\eta_p^2 = 0.42$)
Maillet et al. (2020)	N=36[4]	SART with face stimuli (visual)	Experience sampling (probe)	N170 (lateral parieto-occipital) P3 (centro-parietal)	N170 n.s.	P3 ↓ ($\eta_p^2 = 0.28$)
Martel et al. (2019)[6]	N=26	SART (visual)	Experience sampling (probe)	P1/N1/P2 (parieto-occipital) P3 (centro-parietal) *tested all electrodes	P1 ↓ P2 ↓ N1 n.s.	P3 ↓
Smallwood et al. (2008)	N=22	SART (visual)	Experience sampling (probe)	P3 (centro-parietal)	-	P3 ↓
Xu (2018) E4[6]	N=40	Cued-recall memory task (visual)	Experience sampling (probe)	P1 (occipital) Late positive slow wave (parietal)	P1 ↓	Late, positive slow wave ↓
Xu et al., (2018)	N=29	Cued-recall memory task (visual)	Experience sampling (probe)	P1 (parieto-occipital) P2 (parietal) Late positive slow wave (parietal)	P1 n.s. P2 ↓ ($\eta_p^2 = 0.13$)	Late, positive slow wave ↓ ($\eta_p^2 = 0.17$)

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Table 1 (*continued*)

Reference	Final Sample Size	Task (modality)	MW Measure	EEG Measures[2]	Early ERPs[1]	Late ERPs[1]
Braboszcz and Delorme (2011)	N=12	Breath counting task + passive tones (kinesthetic, auditory)	Experience sampling (self-report)	N1 (called MMN in study, right frontal) P2 (fronto-central) *tested all electrodes	N1 ↓ P2 ↑	
Barron et al. (2011)	N=25 (high, n=8; med, n=9; low, n=8)	Three-stimulus oddball task (visual)	Retrospective (based on DSSQ[5], used for categorizing participants into high, medium, and low MW groups)	P3a (fronto-central) P3b (centro-parietal)	-	P3a ↓ P3b ↓
Gonçalves et al. (2018)	N=33 (not-MW, n=13; MW, n=20)	Attention network test (ANT) (visual)	Retrospective (based on ReSQ[5], used for categorizing participants into MW and not MW groups)	**time locked to cue and target* P1 (occipital), pN1 (frontal), N1/P3 (parieto-occipital), **time-locked to cue only* pP1 (prefrontal), pN (prefrontal – frontal)	P1 n.s. pN1 n.s. pP1 n.s. N1 n.s.	P3 n.s. pN n.s.
Jankowski and Stróżak (2019)	N=29	recognition memory task (visual)	Retrospective (based on CIQ[5] – task-irrelevant interference)	LPC (left parietal) RF (right frontal) LPN (midline parietal)	-	LPC n.s. RF n.s. LPN n.s.
Pepin et al. (2021)	N=30	Driving simulation task (visual)	Retrospective	N1/P3 (parieto-occipital)	N1 ↓	P3 ↓
Riby et al. (2008)	N=20	Recognition memory task (visual)	Retrospective (based on DSSQ[5], used for categorizing participants into MW and not MW groups)	Left-parietal positive wave (left parietal) Right-frontal positive wave (right frontal) Central-negativity (POz & Pz)	-	Left parietal ↓ (η_p^2 = 0.32) Right-frontal n.s. Central-negativity ↑ (η_p^2 = 0.27)

[1] The direction of effect is referenced to mind wandering compared to on-task states. Effect sizes are displayed in brackets if reported in the original research.
[2] ERP components examined in each study is reported along with corresponding regions examined; if all electrodes were tested, regions reported in brackets indicate those showing significant effects.
[3] SART = sustained attention to response task.
[4] Sample was a control group in a study involving a separate clinical group.
[5] DSSQ = Dundee Stress State Questionnaire; RESQ = Resting State Questionnaire; CIQ = Cognitive Interference Questionnaire.
[6] grey literature: preprint at the time of final submission (Martel et al., 2019) and one dissertation (Xu, 2018).

Table 2
Summary of mind wandering (MW) studies examining spectral measures included in this review, presented by type of MW measure.

Reference	Final Sample Size	Task (modality)	MW Measure	EEG Measures[2]	Delta[1]	Theta[1]	Alpha[1]	Beta[1]	Gamma[1]
Andrillon et al. (2021)	N=26	SART (face stimuli + digits; visual)	Experience sampling (probe)	Delta (number and amplitude of sleep-like slow wave: frontal) *tested all 63 electrodes	↑	-	-	-	-
Arnau et al. (2020)	N=33	Switching task (visual)	Experience sampling (probe)	**non stim-locked* Delta, Theta, Alpha **stim-locked* Theta, Alpha *tested all 32 electrodes; effects spanned all regions, maximal over centro-parietal	↑	↑	↑	-	-
Baird et al. (2014)	N=14	0-back vigilance task (visual)	Experience sampling (probe)	Theta (phase: parietal) Alpha (frontal) Beta (frontal, early; centro-parietal, late) *tested frontal, central, parietal, occipital regions	n.s.	↓	↓	↓	-
Baldwin et al. (2017)	N=9	Driving task (visual) + thought probe (auditory)	Experience sampling (probe)	*tested Fz, averaged 10s pre-probe	-	n.s.	↑	-	-
Boudewyn and Carter (2018)	N=34	Audiobook listening (auditory)	Experience sampling (probe)	*tested Fz, averaged 10s pre-probe	-	n.s.	↑	n.s.	-
Broadway et al. (2015)	N=22	Reading task (visual)	Experience sampling (probe)	**pre-stimulus* Alpha (occipital)	-	-	n.s.	-	-
Compton et al. (2019)	N=50	Stroop task (visual)	Experience sampling (probe)	Alpha (maximal over parietal, averaged 2s, 5s, 10s pre-probe) *tested all 12 electrodes	-	-	↑ (η_p^2 = 0.19-45)	-	-
Dhindsa et al. (2019)	N=15	Listening to lecture (visual and auditory)	Experience sampling (probe)	**averaged 10s pre-probe* results presented for group-level analyses	-	n.s.	n.s.	n.s.	-
Ibáñez-Molina and Iglesias-Parro (2014)	N=11	Audiovisual task (visual and auditory)	Experience sampling (probe)	*FFT, averaged 50s pre-probe	n.s.	n.s.	n.s.	n.s.	-
Jin et al. (2019)	N=18	SART (visual); Visual search task (visual)	Experience sampling (probe)	Theta (parieto-occipital coherence) Alpha (frontal & parieto-occipital)	-	↑ (η_G^2 = 0.16)	↑ (η_G^2 = 0.23 - 0.30)	-	-
Kam et al. (2021)	N=39	Categorization task (visual)	Experience sampling (probe)	Alpha (Oz, non stim-evoked)	-	-	↑	-	-
Kirschner et al. (2012)	N=15 (E1) N=10 (E2)	SART (visual)	Experience sampling (probe)	**intra-regional* Theta/Gamma (occipital, stim-evoked) Alpha/Gamma (right temporal, non stim-evoked) **inter-regional* Theta/Alpha/ Gamma (occipital and other regions; right temporal and other regions)	-	↓ (intra, occipital) ↓ (inter,occipital) ↑ (inter, temporal)	↑ (intra, temporal) ↓ (inter,occipital ↑ (inter, temporal)	-	↓ (intra, occipital) ↑ (intra, temporal) ↓ (inter, occipital) ↑ (inter, temporal)
Macdonald et al. (2011)	N=11	Visual detection task (visual)	Experience sampling (probe)	Alpha (parieto-occipital, pre-stimulus)	-	-	↑ (η_p^2 = 0.28)	-	-
Martel et al. (2019)4	N=26	SART (visual)	Experience sampling (probe)	Delta/Theta (FCz, non stim-evoked) Alpha/Beta (PO3/PO4, stim-evoked)	↑	↑	↓	↓	-

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Table 2 (*continued*)

Reference	Final Sample Size	Task (modality)	MW Measure	EEG Measures[2]	Delta[1]	Theta[1]	Alpha[1]	Beta[1]	Gamma[1]
Polychroni et al. (2021)	N=39	Audiobook listening task (auditory)	Experience sampling (probe – on task, MW with awareness (tune-out) and without awareness (zone-out))	Delta (midline central, zone-out MW) Theta (right frontal & left temp-parietal, zone-out MW) Alpha (bilateral frontal and posterior, tune & zone out MW) *tested all 64 electrodes; averaged 10s pre-probe	↑ (g = 1.43)	↑ (g = 0.83)	↑ (g = 0.66-0.86)	-	-
Qin et al. (2011)	N=14	SART (visual)	Experience sampling (probe)	*tested all 62 electrodes; averaged 4s pre-probe	-	n.s.	n.s.	n.s.	n.s.
Rodriguez-Larios and Alaerts (2021)	N=25	Breath focus task (kinesthetic)	Experience sampling (probe)	Theta amplitude (all electrodes) Alpha amplitude (right temporo-occipital) Alpha:theta ratio and phase synchrony *tested all 32 electrodes; averaged 5s pre-probe	-	↑ (amplitude)	↓ (amplitude) ↑ (alpha:theta ratio & synchrony)	-	-
Swart et al. (2020)	N=24[3]	Reading task (visual)	Experience sampling (probe)	Theta-beta ratio fluctuations (frontal, early stim-evoked; correlation with MW frequency)	-	n.s.	-	-	-
Wamsley and Summer (2020)	N=27	SART (visual)	Experience sampling (probe)	*tested Fz, pre-stimulus	↓ (d = 1.38)	↓ (d = 0.61)	↑ (d = 0.82)	n.s.	-
Braboszcz and Delorme (2011)	N=12	Breath counting task with passive tones (kinesthetic and auditory)	Experience sampling (self-report)	**averaged 10s pre self-report* Delta (fronto-central) Theta (maximal, parieto-occipital) Alpha (occipital) Beta (frontal) **stim-locked* Delta (frontal and occipital) Theta (frontal) Beta (parieto-occipital) * tested all 124 electrodes	↑ (10s + stim-evoked)	↑ (10s + stim-evoked)	↓ (10s)	↓ (10s) ↑ (stim-evoked)	-
Cunningham et al. (2000)	N=9	Vigilance task (visual)	Experience sampling (self-report)	**averaged 30s pre- and post-self-report to reflect MW and on-task states* Beta:alpha, beta:[alpha+theta] ratio (centro-parietal)	-	-	-	↓	-
van Son et al. (2019a)	N=26	Breath counting task with passive tones (kinesthetic, auditory)	Experience sampling (self-report)	**averaged 6s pre- and post-self-report to reflect MW and on-task states* *tested frontal sites	-	↑ (theta, d=0.47; theta:beta ratio, d = 1.13)	↓ (d = 0.63)	↓ (d = 0.74)	-
van Son et al. (2019b)	N=26[3]	Breath counting task with passive tones (kinesthetic, auditory)	Experience sampling (self-report)	**averaged 6s pre- and post-self-report to reflect MW and on-task states* *tested frontal sites	↑ (η_p^2 = 0.27)	↑ (theta, η_p^2 = 0.35; theta:beta ratio, η_p^2 = 0.53)	↓ (η_p^2 = 0.41)	↓ (η_p^2 = 0.43)	-

[1] The direction of effect is referenced to mind wandering compared to on-task states. Effect sizes are displayed in brackets if reported in the original research.

[2] Frequency power examined in each study is reported along with a) corresponding regions and b) time intervals of significant effects, which was categorized as pre-stimulus, stimulus-locked ("stim-locked", default option if not specified), non stimulus-locked (for effects occurring during inter-trial interval), and averaged across stimulus during the period preceding thought probes. For one study that examined connectivity (Kirschner et al., 2012), analyses were categorized as within-region ("intra-regional") or across-region ("inter-regional").

[3] Sample consisted of only female or male participants.

[4] grey literature: preprint at the time of final submission.

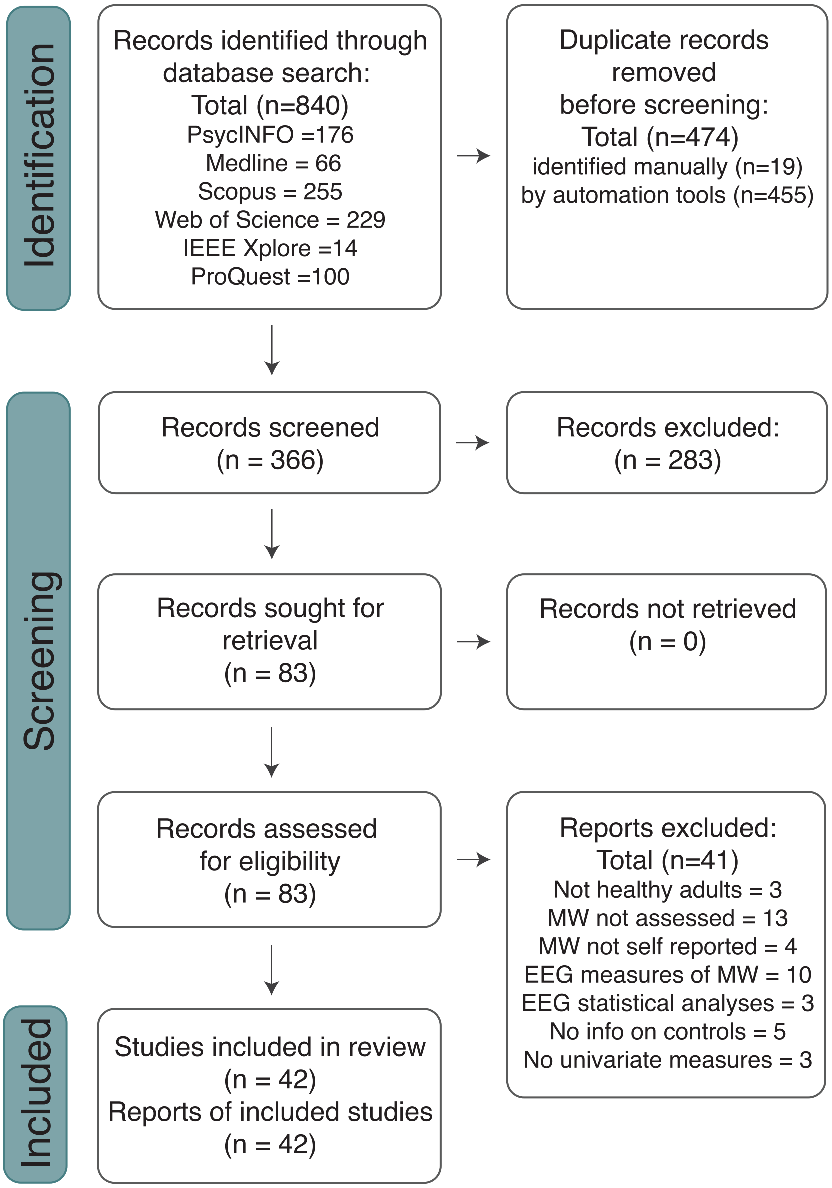

Fig. 1. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram, summarizing search results and the inclusion/exclusion process.

during periods of mind wandering compared to on-task states. Four of these papers used variations of the sustained attention to response task (SART; Jin et al., 2019; Kam et al., 2014a, 2011 E1,E2,E3; Martel et al., 2019), in which participants were asked to respond to frequently occurring non-target numbers and withhold their response to an infrequent target number (Robertson et al., 1997). Others used the N-back working memory task (Baird et al., 2014; Bozhilova et al., 2021), a vigilance task (Bozhilova et al., 2021), a visual search task (Jin et al., 2019), and a cued-recall memory task (Xu, 2018 E4) to elicit the occipital P1. Since several studies implemented more than one task, this mind wandering effect on P1 was observed in 11 tasks across these seven studies. Fig. 3 presents an example of this significant mind wandering effect on P1.

The remaining four studies reported null results, showing no significant difference in P1 amplitude between on-task and mind wandering states. While one of these studies also used the SART, it involved face stimuli instead of numbers which more prominently elicits the N170 ERP component (Denkova et al., 2018). Two other studies presented one word at a time during a reading task (Broadway et al., 2015) and during the study phase of a cued-recall memory task, in which results showed only trend levels of a decrease in posterior P1 amplitude during mind wandering ($p = .085$; (Xu et al., 2018). Finally, one study implemented a between-subject comparison based on participants' retrospective reports of whether they spent more time on-task or mind wandering during the Attention Network Task (Gonçalves et al., 2018). This retrospective approach has the benefit of not interrupting the task and natural flow of attention states (Smallwood and Schooler, 2006); however, there are several issues with this approach that may explain the null findings. In particular, retrospective reports may not provide an accurate assessment of time spent in certain attention states; moreover, the ERP measures averaged across the entire task do not uniquely capture the manifestation of mind wandering states in the moment. No studies reported a larger P1 during mind wandering relative to on-task states.

N1. The N1 is often reported as an index of sensory level auditory processing measured across frontocentral midline sites and visual processing measured across the occipital sites. Six out of the nine studies that examined N1 found that mind wandering was associated with an attenuation of the N1 amplitude relative to on-task states. None of these studies reported the opposite pattern; however, three reported null results. The six studies that showed N1 attenuation during mind wandering used a variety of visual and auditory stimuli to elicit the N1. Some studies examined the fronto-central N1, which was time-locked to tones that participants passively listened to as part of the auditory

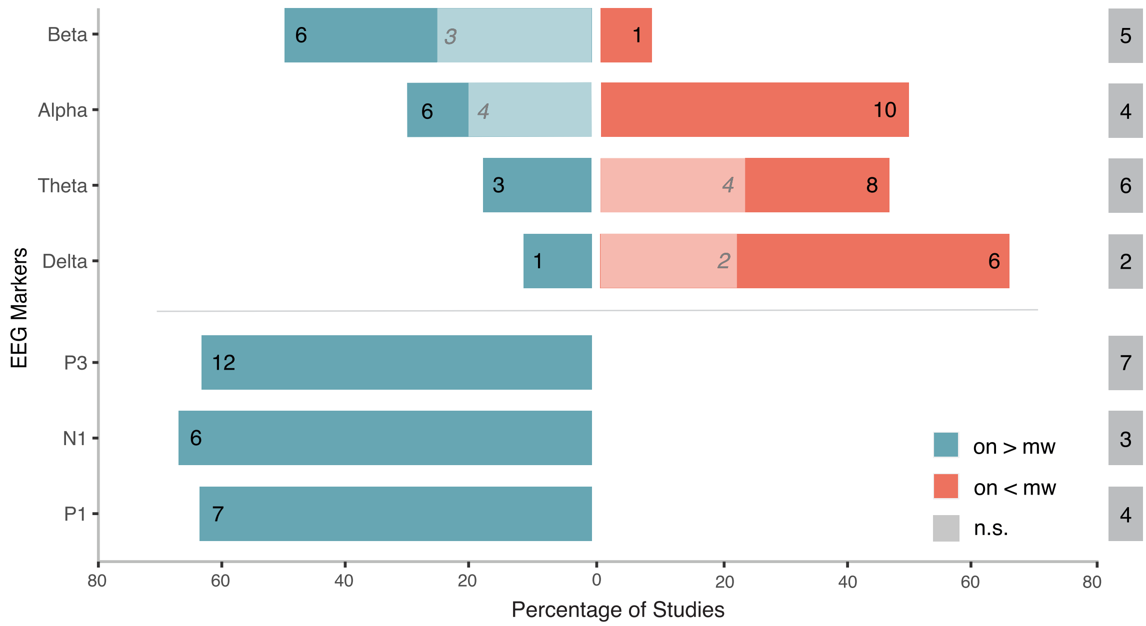

Fig. 2. Graphical summary of the effects of mind wandering on canonical ERP components (P1, N1, and P3) and spectral features (delta, theta, alpha, and beta). The direction of effect indicates whether mind wandering (mw) showed decreased (in teal color) or increased (in coral color) magnitude compared to on-task (on) periods. The length of bars reflects percentage of studies reporting those effects, and the numerical value at the end of the bars reflect the total number of studies reporting those effects. The lighter parts of these colored bars, along with the italicized numerical value within this lighter section, reflect the number of studies that implemented internally oriented tasks reporting those effects. The darker parts reflect studies that implemented externally oriented tasks. The value in the grey boxes on the right indexes the number of studies with non-significant (n.s.) findings, all of which used externally oriented tasks.

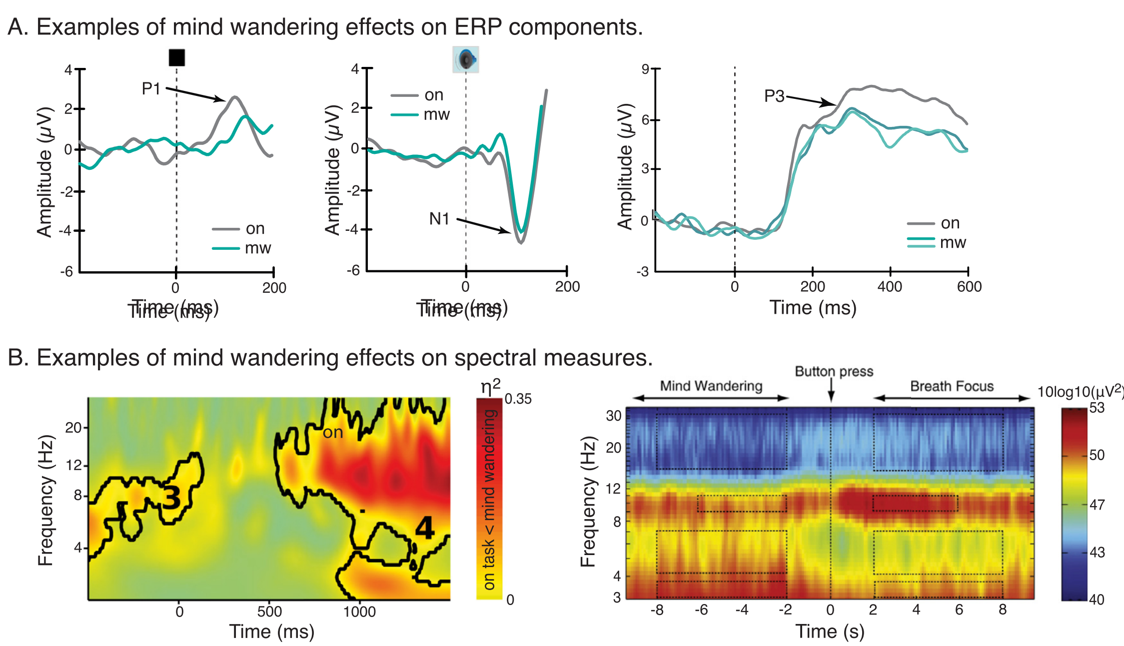

Fig. 3. Example EEG results from studies included in this review. A) Attenuation in P1 (left), N1 (middle), and P3 (right) ERP during mind wandering (mw). Figures adapted from Kam et al., 2011; Smallwood et al., 2008 with permission from Journal of Cognitive Neuroscience. B) Mind wandering has been generally linked to increased delta, theta, and alpha, and decreased beta, especially in traditional tasks in which these measures are elicited by external stimulus (left). Warmer colors indicate greater activity during mind wandering compared to on-task states. In contrast, internally oriented breath focus tasks have generally reported decreased alpha during mind wandering compared to breath focus (right). Figures adapted from Arnau et al., 2020 with permission from Psychophysiology, and Braboszcz and Delorme, 2011 from Neuroimage.

oddball paradigm (Braboszcz and Delorme, 2011; Kam et al., 2013) or to task-irrelevant tones during SART (Kam et al., 2011 E2). Others focused on the occipital N1 time-locked to visual stimuli during SART and a visual search task (Jin et al., 2019) and simulated driving (Pepin et al., 2021), as well as to single words presented during a reading task (Broadway et al., 2015).

Of the three studies that reported no difference in N1 amplitude between on-task and mind wandering states, one used visual stimuli during SART to elicit the occipital N1 (Martel et al., 2019). Another study with null results adopted a between-subject comparison approach as previously described and compared individuals who retrospectively reported having spent more time focusing on-task or mind wandering

(Gonçalves et al., 2018). The third study only presented an auditory probe that prompted experience sampling measures during a driving task that exclusively displayed visual stimulus (Baldwin et al., 2017). Given this tone always signaled a pause on the driving task with the occurrence of thought probes that required participants to report their attention state, the N1 response to this tone inherently captures a different process related to task conclusion, as compared to ongoing task performance.

P2. Following the sensory level ERP components, the P2 captures attention and memory related perceptual processes and can be modulated by physical properties of sensory stimuli. Of the three studies that examined P2, two reported significantly reduced parieto-occipital P2 amplitude during mind wandering compared to on-task states. These studies used tasks in the visual modality, including the SART (Martel et al., 2019) and cued-recall memory task (Xu et al., 2018). The third study reported the opposite pattern and involved auditory stimuli, revealing a larger frontal P2 time-locked to task-irrelevant tones when mind wandering during an internally oriented breath counting task (Braboszcz and Delorme, 2011). This is the only study that reported an opposite pattern of increased amplitude during mind wandering across all studies examining ERP components.

Other early ERP components. In addition to canonical sensory ERP components, several other components that were uniquely elicited by their corresponding task were examined. For instance, a study that used face stimuli in a SART paradigm found that mind wandering was linked to decreased N170 amplitude compared to on-task states (Denkova et al., 2018). Using an integration of face and scene stimuli overlaid on each other in a SART paradigm, a subsequent study did not replicate these results (Maillet et al., 2020). The authors suggested this null finding may be attributable to the automaticity of face processing; yet, this explanation is inconsistent with the previously reported significant effect of mind wandering on face processing as indexed by N170 (Denkova et al., 2018). Another study reporting null results in other early ERP components examined attentional state differences using experience sampling in the early frontal positive wave in response to images conveying painful situations (Kam et al., 2014b). Finally, an aforementioned study that compared between subjects based on retrospective reports of attentional focus also did not observe significant differences between attention states in other ERP components, including the frontal pN1 and pP1 during the attention control task (Gonçalves et al., 2018).

3.2.2. Mind wandering effect on later ERP components

P3. The most commonly examined ERP component is the P3, which typically peaks around 300-500ms and reflects a wide range of high-level cognitive processes (Polich, 2003). Of the 19 studies that examined the P3 component, 12 reported a reduction in the P3 amplitude during periods of mind wandering relative to on-task (as illustrated in an example study in Fig. 3). With the exception of one study that examined P3a elicited by a tone that indicates thought probe occurrence (Baldwin et al., 2017) and one study that examined P3a and P3b during a visual oddball task (Barron et al., 2011), all studies exclusively focused on the posterior P3b elicited by visual stimuli. Most of the tasks used were variations of the SART (Jaswal et al., 2019; Jin et al., 2019; Kam et al., 2011 E1; Maillet et al., 2020; Martel et al., 2019; Smallwood et al., 2008). Other studies implemented a time estimation task with visual performance feedback (Kam et al., 2012), a simulated driving task (Pepin et al., 2021), a visual search task (Jin et al., 2019), and variations of visual detection tasks (Barron et al., 2011; Kam et al., 2021; Macdonald et al., 2011). These studies reveal the multitude of cognitive processes that are disrupted, including target detection and performance monitoring, during mind wandering as captured by the P3.

No studies reported greater P3 amplitude during mind wandering, and the remaining seven studies all reported no attentional state differences in P3 amplitude. Among these studies, some used the SART with numeric stimuli (Kam et al., 2015, 2014a) or face stimuli (Denkova et al., 2018). Others used a reading task (Broadway et al., 2015), an affective task with images conveying painful and non-painful situations (Kam et al., 2014b), a working memory task (Bozhilova et al., 2021), and variants of attention and vigilance tasks (Bozhilova et al., 2021; Gonçalves et al., 2018).

Other later ERP components. Aside from the P3, other late latency ERP components have also been examined. In the context of memory, three studies that used a semantic memory recall task reported that mind wandering was tied to a significant attenuation in the late parietal positive wave (Riby et al., 2008; Xu, 2018; Xu et al., 2018). However, another memory study found that mind wandering (as indexed by retrospective reports of task-irrelevant interference during the task) did not account for variance in any memory-related ERP components (Jankowski and Stróżak, 2019). In examining the feedback error-related negativity time-locked to visual performance feedback during a time estimation task, one study found that amplitude of this ERP component was reduced while mind wandering (Kam et al., 2012). Another study focused on the late frontal slope elicited by images conveying painful situations and reported that mind wandering was linked to reduced amplitude of this slope compared to on-task periods (Kam et al., 2014b). Finally, two studies did not find any attentional state differences in other late latency ERP components, including the frontal pN during the attention control task using retrospective measures of mind wandering in an aforementioned study (Gonçalves et al., 2018), and the centro-parietal late positive potential during a visual SART using experience sampling (Jaswal et al., 2019).

3.3. Spectral Correlates of Mind Wandering

In the following section, we report the summary of EEG spectral correlates as a function of each canonical frequency band. Among the 23 publications, a comparable number of studies selected specific frequency bands a priori or examined multiple frequency bands using a data driven approach. The most commonly investigated frequency bands are theta (17 studies) and alpha (20 studies), followed by beta (11 studies) and delta (9 studies). We also summarize the studies separately for those using externally versus internally oriented tasks. All four studies that used an internally oriented task used a breath focus or counting task. They not only differed in the nature of the task stimuli, but they also adopted an analysis approach that differed from studies using an external task. In particular, the spectral measures in these studies were often not time-locked to specific stimuli and averaged across the five to ten seconds in reference to the reported instances of mind wandering. The remaining 19 studies used various externally oriented tasks and examined both stimulus-evoked and non-stimulus evoked measures of spectral activity.

3.3.1. Mind wandering effect on frequency bands

Delta. Only a handful of mind wandering studies have examined the delta band (usually indexed by activity in 1-4 Hz). Among the externally oriented tasks, four of seven studies that reported a significant attentional state difference have found higher delta activity primarily over fronto-central sites during mind wandering relative to on-task states. These studies implemented a switching task (Arnau et al., 2020), the SART (Andrillon et al., 2021; Martel et al., 2019), and an audiobook listening task (Polychroni et al., 2021). They primarily examined tonic delta activity, in which the signal was not time-locked to specific stimuli (Polychroni et al., 2021) or during intervals that were at least 1s past stimulus onset (Arnau et al., 2020; Martel et al., 2019). Notably, one group uniquely quantified activity in this frequency range in the form of sleep-like slow wave activity during SART, and found this local sleep marker occurred during mind wandering (Andrillon et al., 2021). In contrast to these patterns, one study found that mind wandering was tied to decreased pre-stimulus frontal delta activity compared to on-task states during SART (Wamsley and Summer, 2020). Two studies reported no significant attentional state differences, one of which used a 0-back working memory task (Baird et al., 2014) to elicit delta band activity. The second one used a viewing task involving mismatched audio-visual stimuli, and computed power spectral density measures averaged across 50 sec epochs (Ibáñez-Molina and Iglesias-Parro, 2014). This method implemented on a long epoch may have washed out potential attentional differences by discounting temporal fluctuations in the signal, which may explain their null results.

Among those using the internally oriented breath focus task, both studies examined tonic delta activity and averaged the EEG signal across the six to ten seconds in reference to the self-reported instance of mind wandering (Braboszcz and Delorme, 2011; van Son et al., 2019b). Similar to the external tasks, both reported higher tonic delta activity primarily over fronto-central sites during mind wandering relative to on-task states.

Theta. Theta band is typically characterized by activity in 4-8 Hz. Among four of the 13 studies that used externally oriented tasks, there was evidence for greater theta band activity during mind wandering compared to on-task states (Arnau et al., 2020; Martel et al., 2019; Polychroni et al., 2021) as well as greater theta coherence between parietal and occipital sites (Jin et al., 2019). While one of these four studies reported significant attentional differences in stimulus-evoked theta coherence over posterior sites (Jin et al., 2019), the remaining three reported tonic theta activity at fronto-central sites and across distributed regions. These studies used visual stimuli in the SART (Jin et al., 2019; Martel et al., 2019), a visual search task (Jin et al., 2019), and a switching task (Arnau et al., 2020), as well as auditory stimuli while listening to audiobooks (Polychroni et al., 2021) to elicit theta activity. Fig. 3 presents an example of this significant mind wandering effect on theta.

Three studies reported reduced theta activity during mind wandering compared to on-task states, of which two examined pre-stimulus theta over frontal sites (Wamsley and Summer, 2020) and stimulus-evoked theta over occipital sites (Kirschner et al., 2012) during SART. The third reported reduced inter trial phase consistency in parietal theta during the 0-back working memory task (Baird et al., 2014). Evidently, theta band findings are among the least consistent across all frequency bands, as indicated by the increase and decrease in theta activity during mind wandering reported in different studies using the same SART (Jin et al., 2019; Kirschner et al., 2012; Martel et al., 2019; Wamsley and Summer, 2020).

The remaining six of the 13 studies found no significant difference between on-task and mind wandering states. Some used stimuli or testing environments that were more ecologically valid, including a driving task (Baldwin et al., 2017), a viewing task involving mismatched naturalistic audio-visual stimuli (Ibáñez-Molina and Iglesias-Parro, 2014), and listening to an audiobook (Boudewyn and Carter, 2018) or a live lecture (Dhindsa et al., 2019). Others used traditional lab-based tasks, such as the SART (Qin et al., 2011). Another study with null results found that theta-beta ratio variance did not correlate with the number of mind wandering reports during a reading task (Swart et al., 2020). These studies reporting null findings all averaged the electrophysiological response over an extended time period across multiple stimuli. The absence of significant attentional differences in some of these studies may be attributed to the use of less sensitive measures as previously discussed (Ibáñez-Molina and Iglesias-Parro, 2014) or methodological issues associated with highly ecologically valid settings (Dhindsa et al., 2019; Swart et al., 2020), including restricting analyses to single electrodes during ecologically valid tasks which may show more spatially distributed patterns (Baldwin et al., 2017; Boudewyn and Carter, 2018; Wamsley and Summer, 2020).

All of the four studies that used the internally oriented breath focus task reported higher levels of theta activity during mind wandering compared to on-task states (Braboszcz and Delorme, 2011; Rodriguez-Larios and Alaerts, 2021; van Son et al., 2019a, 2019b). One of these studies (Rodriguez-Larios and Alaerts, 2021) did not rely on the self-caught experience sampling measure of mind wandering. In addition to measuring theta activity, two of these studies also reported higher frontal theta-beta ratio during mind wandering (van Son et al., 2019a, 2019b).

Alpha. Activity in the alpha band is the strongest theoretically driven and most commonly examined frequency band in mind wandering. Typically assessed between 8 to 12Hz (up to 14Hz), alpha band activity has been shown to increase when eyes are closed or open during rest, resulting in its original interpretation as a marker of alertness. Among the 16 studies that implemented externally oriented tasks, 10 reported an increase in alpha band activity during periods of mind wandering relative to on-task (as shown in an example study in Fig. 3). While many found this attentional state difference across posterior sites (e.g., (Baldwin et al., 2017; Compton et al., 2019; Jin et al., 2019; Kam et al., 2021; Macdonald et al., 2011; Polychroni et al., 2021), this effect was also observed over fronto-central and temporal sites (e.g., Arnau et al., 2020; Boudewyn and Carter, 2018; Jin et al., 2019; Kirschner et al., 2012; Polychroni et al., 2021; Wamsley and Summer, 2020). These studies used a diverse range of visual and auditory stimuli embedded in highly controlled tasks (including the SART, the Stroop task, and the switching task) as well as ecologically valid tasks (including driving and listening to audiobooks). Apart from one study that examined stimulus-evoked alpha activity (Jin et al., 2019), the significant effects in the remaining studies were observed during pre-stimulus intervals or periods not time-locked to external stimulus. These findings converge on the notion that increased alpha band activity as a marker of mind wandering is unlikely to be specific to a particular task.

In contrast, two of the 16 studies found that mind wandering was associated with lower alpha band activity. They used a 0-back working memory task (Baird et al., 2014) and the SART (Martel et al., 2019), and observed lower stimulus-evoked alpha during mind wandering over similar regions. In the remaining four studies, alpha band activity did not differentiate between attentional states. Three of these studies did not find significant attentional differences in alpha and any of the other measured frequency bands during the SART (Qin et al., 2011), live lecture viewing (Dhindsa et al., 2019), and a viewing task using mismatched audio-visual stimuli (Ibáñez-Molina and Iglesias-Parro, 2014). The fourth study examined a short pre-stimulus interval of 50 msecs during a reading task, which may not be a sufficiently long period to capture changes in alpha activity over time (Broadway et al., 2015).

Among the four studies using an internally oriented task, all reported reduced alpha activity not time-locked to specific stimuli during mind wandering and observed these effects over frontal channels (van Son et al., 2019a, 2019b) or posterior channels (Braboszcz and Delorme, 2011; Rodriguez-Larios and Alaerts, 2021).

Beta. Similar to the delta band, less effort has been dedicated to examining the beta band which is usually indexed by 15-30Hz activity. Among the eight studies examining beta using externally oriented tasks, three found that mind wandering was associated with reduced fronto-central beta activity (Baird et al., 2014; Martel et al., 2019) and parietal beta-alpha ratio (Cunningham et al., 2000) relative to on-task. Cunningham and colleagues (2000) interpreted beta-alpha ratio as a marker of alertness, with lower ratios reflecting decreased alertness. These studies used a 0-back working memory task (Baird et al., 2014) or the SART (Martel et al., 2019) in which beta activity was elicited by visual stimuli. Finally, a perceptual discrimination task was used in which the beta-alpha ratio was time-locked to the visual stimuli (Cunningham et al., 2000).

The remaining five studies using externally oriented tasks did not show any significant differences in beta activity between on-task and mind wandering states. These studies used experimental tasks including the SART (Qin et al., 2011; Wamsley and Summer, 2020) as well as ecologically valid tasks including listening to audiobooks or lectures (Boudewyn and Carter, 2018; Dhindsa et al., 2019; Ibáñez-Molina and Iglesias-Parro, 2014). Remarkably, two of these studies only examined a single electrode during the SART (Wamsley and Summer, 2020) and an audiobook listening task (Boudewyn and Carter, 2018), while the other three did not find significant attentional differences in any of the measured frequency bands (Dhindsa et al., 2019; Ibáñez-Molina and Iglesias-Parro, 2014; Qin et al., 2011).

Among those using an internally oriented task, all three studies averaged the beta signal across a time interval (i.e., 6-10 secs) in reference to self-reported instances of mind wandering not time-locked to external stimulus (Braboszcz and Delorme, 2011; van Son et al., 2019a, 2019b). Consistent with findings from external tasks, they all reported lower levels of fronto-central beta activity during mind wandering compared to on-task states. One of these studies also examined beta activity time-locked to passively presented task-irrelevant tones and observed significantly higher tone-evoked beta activity during mind wandering compared to on-task states over parieto-occipital sites (Braboszcz and Delorme, 2011).

Gamma. Only two studies examined gamma band, typically referring to activity between 30 and 50Hz (and up to 70Hz), and both implemented externally oriented tasks. Using experience sampling during SART, one found reduced stimulus-evoked occipital gamma and greater gamma activity over the right middle temporal cortex regardless of stimulus onset during mind wandering (Kirschner et al., 2012). The other study did not find evidence for attentional state difference in activity in the gamma band (or any other examined frequency bands as previously mentioned) during the SART (Qin et al., 2011).

3.4. Additional EEG Markers of Mind Wandering

Beyond ERP and spectral measures, two papers examined other EEG markers of mind wandering. One study focused on the measure of fractal dimension which the authors interpret as a marker of complexity in the EEG signal (Ibáñez-Molina and Iglesias-Parro, 2014). Although they did not find significant attentional differences in frequency power, they observed increased fractal dimension during mind wandering. The second study used face stimuli embedded in the SART to examine EEG microstates, which are characterized by unique topographic voltage configurations (Zanesco et al., 2020). They found microstate C occupied more time whereas microstate E occupied less time in the pre-stimulus intervals during mind wandering. Given past findings have localized the generators of microstate C in regions within the default mode network, and generators of microstate E in regions within the midcingulo-insular network, the authors interpreted their findings as distinct functional brain states that occur during mind wandering, which is in line with the functional roles of large-scale networks in mind wandering (Fox et al., 2015).

4. Discussion

In this systematic review, we synthesized studies published in the last two decades using EEG to establish the electrophysiological markers of mind wandering in healthy adults. Despite the substantial methodological heterogeneity in these studies, several electrophysiological patterns emerged during periods of mind wandering. The most consistently observed pattern lies in ERP amplitude, in which mind wandering was associated with a reduction in the magnitude of the canonical sensory and cognitive ERP components (i.e., the P1, N1, and P3). While results involving spectral markers were somewhat mixed, they generally converge on greater activity in the low frequency range of delta, theta, and alpha, and a decrease in beta band activity during mind wandering. The opposing findings in spectral measures likely reflect the context-dependent effects of mind wandering related to external versus internal task orientation. Together, our results suggest that these electrophysiological markers index different aspects and processes of mind wandering, which we incorporate into an electrophysiological account of mind wandering below.

4.1. ERP amplitude reduction as robust marker of mind wandering

Our review of ERP studies provides strong evidence that an attenuation in the amplitude of ERP components is a reliable marker of mind wandering. The majority of these papers (60-67%) have revealed significantly reduced amplitude in their corresponding ERP components during mind wandering. Notably, there are no reports of the opposite finding across all studies, except for one characterizing mind wandering with an increased P2 in response to task-irrelevant tones during an internally oriented task (Braboszcz and Delorme, 2011).

The sensory level ERP components are the most robust indicators of mind wandering, suggesting this attention state is associated with disrupted sensory level processing of external stimuli. These results support the perceptual decoupling account of mind wandering (Schooler et al., 2011; Smallwood and Schooler, 2015). This framework purports that in order to facilitate mind wandering, our limited neural resources must be directed away from the external environment and allocated internally, which results in the decoupling of attention from perceptual stimuli during mind wandering. This decoupling process is manifested in reduced amplitudes of sensory level ERP components. For the P1 ERP component, 64% of papers observed reduced amplitude during periods of mind wandering. These studies all used visual stimuli in a variety of target detection and visual search tasks to elicit P1 examined over posterior sites, which uniformly suggests that our sensory level response to visual stimuli is attenuated during mind wandering. Similarly, 67% of papers examining the N1 reported that mind wandering was associated with reduced amplitude, irrespective of whether N1 was elicited by auditory stimuli across fronto-central sites or by visual stimuli across occipital sites. These patterns suggest that mind wandering disrupts sensory response to both visual and auditory stimuli, corroborating our original finding (Kam et al., 2011).

Among the studies reporting null results, most have reported significant attentional differences in other ERP components that were more task-relevant: this includes the N170 in response to face stimuli (Denkova et al., 2018), and late positive wave in a memory task (Xu et al., 2018). The only exception is a study that used a retrospective measure of mind wandering to compare individuals who reported low versus high levels of mind wandering during an attention task, and found no significant differences in any of their five measured ERP components (Gonçalves et al., 2018). Given past studies using other retrospective measures have reported attentional differences in relevant ERP components (Barron et al., 2011; Riby et al., 2008), this suggests that the specific questionnaire used in that study may not have accurately captured mind wandering rates during the task. We will not discuss this study further in subsequent sections. Taken together, these studies lend support to the perceptual decoupling account of mind wandering, providing clear evidence that the attenuating effect of mind wandering on sensory response is observed across tasks and sensory modalities.

As the primary cognitive level ERP component, P3 is a reliable marker of mind wandering. Expanding beyond the perceptual decoupling account, we previously proposed that decoupling from the external environment is not restricted to the sensory level but instead extends to later stages of information processing in our mechanistic account of mind wandering (Kam and Handy, 2013; Handy and Kam, 2015) . This framework is in line with the studies examining P3, 63% of which reported a significant decrease in P3 amplitude during mind wandering. Many of these elicited the parietal P3b using visual stimuli in a variety of tasks, including the original version of SART and other detection tasks, visual search, simulated driving, and performance monitoring tasks. Similar to the results involving sensory ERP components, this suggests that mind wandering disrupts a wide range of cognitive level processes involving external stimulus across contexts, expanding beyond the original finding (Smallwood et al., 2008).

Our review suggests that several factors play a role in the variable robustness of the mind wandering effect on P3, including sample size, the complexity of stimulus presentation and task-relevance of P3. Perhaps the most puzzling null results concern the studies implementing SART, given the mixed findings of mind wandering effects reported during that task. One potential factor explaining null findings is the lack of power due to small sample sizes in the earlier studies, ranging from 12 to 15 (Kam et al., 2014a, 2011 E2, E3). Moreover, the mixed findings across studies may be related to the complexity of stimulus presentation. Specifically, the attention effect on P3 appears to be most robust when elicited by less complex stimuli, as in the original version with a single digit presented at fixation (Smallwood et al., 2008). Once additional task-irrelevant stimuli were presented alongside targets during SART (as in, Kam et al., 2014a, 2011 E2, E3), the pattern was still visually observed in P3 but the difference between on-task and mind wandering periods was no longer statistically significant. Another factor that may account for these null findings is the relevance of P3 to the task-at-hand. Specifically, several studies that found no difference in P3 reported significant differences in ERP components that were more task-relevant (Denkova et al., 2018; Kam et al., 2014b). This highlights the specificity of the mind wandering effect; that is, mind wandering does not appear to impose a blanket effect on all ERP components, but rather selectively disrupts the process most relevant to the task-at-hand. Taken together, these patterns suggest that the more complex the stimulus presentation and the less relevant P3 is to the task, the less robust the effect of mind wandering on P3 amplitude. Comparatively, studies involving less complex stimuli in which P3 is directly relevant to the task demonstrate that mind wandering is reliably associated with reduced P3 amplitude. These findings corroborate the mechanistic account of neurocognitive consequences of mind wandering (Kam and Handy, 2013; Handy & Kam, 2015), suggesting that the attenuation of cognitive response to external stimuli observed across contexts helps facilitate mind wandering.

Among other ERP components, the ones occurring at later stages of processing show more robust patterns than those occurring at earlier stages. For example, three of four studies examining memory-related ERP components characterized by a late positive wave over parietal sites found a decrease in amplitude during mind wandering (Riby et al., 2008; Xu, 2018; Xu et al., 2018). While these results are promising, more evidence beyond these three studies is needed to establish the reliability of this effect. Studies have also reported a similar mind wandering effect on other task-relevant ERP components, such as the feedback error related negativity as an index of performance monitoring (Kam et al., 2012) and a late frontal slope in response to images conveying pain (Kam et al., 2014b). The studies that did not find significant differences in any of their examined ERP components have used different retrospective measures of mind wandering (Gonçalves et al., 2018; Jankowski and Stróżak, 2019).

In contrast to these reliable patterns, other non-canonical ERP components occurring earlier in the processing stream show more mixed results. Specifically, while two studies found reduced P2 amplitude during mind wandering in a visual task (Martel et al., 2019; Xu et al., 2018), one aforementioned study found increased P2 amplitude in response to task-irrelevant auditory tones (Braboszcz and Delorme, 2011). Likewise, whereas mind wandering was shown to attenuate N170 in response to face stimuli in one study (Denkova et al., 2018), this effect was not significant in a study that overlaid face images on scene stimuli (Maillet et al., 2020). Differences in task stimuli (e.g., stimulus modality and complexity) appear to account for these mixed findings.

Taken together, studies examining the canonical sensory and cognitive level ERP components converge on an attenuation in the P1, N1, and P3 amplitude during mind wandering, corroborating accounts of decoupling from the external environment as a mechanism that facilitates mind wandering. Although some other ERP components such as the those related to memory showed similar patterns as discussed above, less definitive conclusions can be drawn from the paucity of available data.

4.2. *Spectral features as context dependent markers of mind wandering*

In our review of studies involving spectral measures, evidence converged on an overall pattern of increase in delta, theta, and alpha activity, as well as a decrease in beta activity during mind wandering, as illustrated in Fig. 2. A notable portion of papers (47-67%) reported significant attentional differences across the different frequency bands. Although this review reports and discusses each frequency band separately, it is important to note that some studies using data driven approaches have reported that activity in contiguous frequency bands belong to one large significant cluster of data points characterized by the same patterns of mind wandering (e.g., (Arnau et al., 2020; Braboszcz and Delorme, 2011; Polychroni et al., 2021; Qin et al., 2011). These spectral findings are more variable compared to ERP studies, which may be accounted for by the heterogeneity in EEG data preprocessing, electrodes examined, and analytic approach. Importantly, the context related to the external versus internal orientation of the task in which mind wandering was assessed appears to play a role in the direction of the effect of mind wandering on selected spectral markers.

Delta. Although not widely nor selectively examined, activity in the delta band was among the most reliable spectral indicator of mind wandering in the studies reviewed. Activity in this frequency band is often used as an index of wakefulness and sleep states (Muzur et al. 2002). Among the 67% of publications reporting increased delta activity during mind wandering, the majority observed this over frontal or central sites and one reported this pattern across all scalp locations (Arnau et al., 2020). While some studies selectively examined frontal sites (van Son et al., 2019a, 2019b), those including all scalp locations have also observed maximal effects over frontal sites (Andrillon et al., 2021; Martel et al., 2019). The effect of mind wandering was observed irrespective of whether tasks were externally or internally oriented. Since all four studies implementing the internally oriented task adopted an analysis approach that averaged delta activity across a time interval not time-locked to any given stimulus, this effect of mind wandering was likely not restricted to stimulus-locked activity as observed in externally oriented tasks. Interestingly, one of these studies focused on a slow wave marker in the delta range interpreted as an indicator of local sleep-like activity that is present during mind wandering (Andrillon et al., 2021). Given frontal delta activity is a local marker of sleep, this increase in delta activity over frontal sites that appears to consistently index mind wandering may reflect a similar state of reduced alertness in the awake brain (Andrillon et al., 2021). This calls into question then whether this frontal delta wave is simply a marker of drowsiness, as opposed to mind wandering. One study that collected drowsiness ratings at task completion reported an absence of a drowsiness effect and a significant effect of mind wandering on EEG measures (Rodriguez-Larios and Alaerts, 2021). Considering they also found the observed effects of mind wandering to be most pronounced in participants who reported to be drowsier, this set of findings suggests that while drowsiness plays a role in accentuating attentional differences, it likely does not account for the increase in frontal delta activity during mind wandering. This observation of a similar EEG marker during mind wandering and sleep states parallels findings of similar functional neuroimaging correlates of daydreaming and dreaming (Fox et al., 2013). Future studies can clarify whether delta band activity uniquely indexes mind wandering as a separate class of cognitive state, and if so, further elucidate whether it serves a mechanistic role in this phenomenon.

Theta. Theta band activity plays an important role in attentional (Helfrich et al., 2018), working memory (Jensen and Tesche, 2002), and executive control processes (Cavanagh and Frank, 2014), as well as autobiographical memory retrieval and future planning (Foster et al., 2013; Fuentemilla et al., 2014), which often characterizes the content of the wandering mind. Among the studies implementing externally oriented tasks, both studies examining stimulus-evoked activity observed reduced theta power and event-related desynchronization over posterior sites during mind wandering time-locked to task-relevant visual stimuli

(Baird et al., 2014; Kirschner et al., 2012). Similar to the ERP results, the decoupling accounts of mind wandering (Handy and Kam, 2015; Smallwood and Schooler, 2015) can explain the findings of reduced stimulus-evoked task-relevant theta activity when the mind wanders away from the external task. In contrast, several studies reported increased theta activity that was not specifically time-locked to external stimuli (Arnau et al., 2020; Martel et al., 2019; Polychroni et al., 2021). Though Arnau and colleagues (2020) observed theta around the onset of an external stimulus, this pattern was also observed prior to the onset of the stimulus extending into the stimulus onset period suggesting the activity may not be uniquely evoked by the stimulus. These contrasting reports of theta activity in external tasks appear to be modulated by whether this activity was time-locked to an external stimulus, and may therefore reflect different aspects of the mind wandering phenomenon.

Studies using an internally oriented task elicited a consistent electrophysiological pattern of mind wandering, within the theta band and beyond. All four studies that implemented breath focus or counting tasks showed greater theta activity during mind wandering at various time intervals and spatial locations (Braboszcz and Delorme, 2011; Rodriguez-Larios and Alaerts, 2021; van Son et al., 2019a, 2019b). While three of these studies used self-report measures of mind wandering, one used probe-caught measures (Rodriguez-Larios and Alaerts, 2021). That these theta effects were also reported during traditional externally oriented experimental tasks involving both probe-caught measures (e.g., Arnau et al., 2020; Polychroni et al., 2019) and self-caught measures (Martel et al., 2019) suggests that an increase in theta activity during mind wandering was not task-specific or reliant on a particular experience sampling measure of mind wandering. The main commonality across these studies appears to be their focus on theta activity that is not time locked to external stimulus.

Interestingly, these studies that focused on non-stimulus locked activity irrespective of whether they used external or internal tasks converged on greater theta activity over frontal and posterior sites during mind wandering. This pattern is consistent with the finding of increased theta connectivity between the fronto-parietal control network and default network during internally oriented attention (Kam et al., 2019), suggesting frontal and posterior theta may tap into control processes important for switching to and facilitating mind wandering. Most studies reported significant effects in these regions while considering all scalp locations, highlighting the spatial specificity of this marker. Additionally, two studies revealed not only increased theta activity, but also increased theta-beta ratio over frontal sites (van Son et al., 2019a, 2019b). They found that higher levels of this metric correlated with lower activation in the executive control network (van Son et al., 2019b), supporting the interpretation of higher frontal theta-beta ratio as a marker of poorer executive control (Angelidis et al., 2016). This interpretation aligns with the framework purporting that mind wandering occurrence reflects a failure of executive control, especially during demanding tasks (Kane and McVay, 2012). Given that the fronto-parietal control network has been shown to connect with default mode network during internal processes (Andrews-Hanna et al., 2014; Dixon et al., 2018; Kam et al., 2019; Spreng et al., 2010), whereas the executive network has been implicated in the lack of awareness of mind wandering occurrence considered to reflect a deeper stage of mind wandering (Christoff et al., 2009), their electrophysiological correlates may also reflect their different functional roles in mind wandering.

Alpha. As the most commonly examined frequency marker of mind wandering, event-related alpha band activity has long been implicated in visual attention and alertness (Klimesch et al., 1998; Sauseng et al., 2005). It is often considered to reflect inhibitory control processes (Klimesch et al., 2007) particularly of task-irrelevant visual information (Foxe and Snyder, 2011; Jensen and Mazaheri, 2010). Given that mind wandering, especially in terms of the stimulus-independent thought conceptualization, involves shifting attention to the internal world thereby effectively turning off the attentional spotlight on the external environment, alpha band is the strongest theoretically motivated candidate for an EEG marker of mind wandering. To that end, increased alpha activity was indicative of mind wandering in 63% of the included publications that used externally oriented tasks. This effect was observed across all scalp locations, in response to visual and auditory stimuli embedded in experimental (e.g., SART and other detection tasks) and ecologically valid tasks (e.g., driving and audiobook listening). Many of these studies reported greater alpha over posterior sites while mind wandering during a visual task.

As an extension of the widely accepted framework of alpha's role in the functional inhibition of task-irrelevant regions during externally oriented selective attention (Foxe and Snyder, 2011; Jensen and Mazaheri, 2010), one potential account of these findings is that alpha activity may also signal the inhibition of external information irrelevant to ongoing thoughts during mind wandering. Remarkably, this effect was observed primarily during time intervals not directly impacted by stimulus-evoked activity and was also reported over frontal, central, and temporal sites in the reviewed studies; therefore, increased alpha activity likely reflects more than just the inhibition of task-irrelevant stimuli in the context of mind wandering. In particular, another account is that alpha activity is a marker for the phenomenon of mind wandering (i.e., when attention is oriented away from the external task and often towards our internal thoughts), an interpretation that seems to align with the proposed role of alpha inter-regional synchronization in internal information processes in working memory (Palva and Palva, 2011). Although future work is needed to clarify the mechanistic role of alpha band activity in mind wandering, its presence over different regions across different time intervals raises the possibility that alpha reflects unique markers of different aspects of this phenomenon.

Although studies using internally oriented tasks report the opposite pattern, they are surprisingly in line with the interpretation of alpha as marker for mind wandering as a form of internal attention. These studies implemented variations of a breath counting or focus task during which attention is directed internally, and they all converged on decreased alpha during mind wandering (Braboszcz and Delorme, 2011; Rodriguez-Larios and Alaerts, 2021; van Son et al., 2019a, 2019b). This may seem to contrast the above mentioned studies at first glance; however, given that the "on-task" breath focus state is associated with attention focused internally on their breathing, mind wandering would be comparatively focused elsewhere possibly on the external environment. From that perspective, the reduced alpha activity during mind wandering may reflect attention that is directed more externally than when attention is focused on the breath. This speculative interpretation aligns with the narrative that higher levels of alpha activity indexes internally oriented attention.

In summary, studies showing increased or decreased alpha activity during mind wandering both support the same account of alpha activity as a reliable marker of mind wandering especially when conceptualized as stimulus-independent thought or internal attention. The main point of consideration is the direction of this effect, which appears to depend on the context in which mind wandering was assessed, specifically with respect to whether the tasks were oriented to the internal or external environment. Moving beyond the characterization of the external and internal focus of attention, we also recently showed that frontal alpha reflects a dynamic pattern of thoughts that move from topic to topic (Kam et al., 2021). This highlights the potential for alpha band activity as a marker beyond mind wandering per se, expanding its role to capturing different types of ongoing thoughts.

Beta. Of the eight studies examining activity in the beta band using externally oriented tasks, three observed decreased beta activity during mind wandering while the others reported null findings. These three studies all focused on stimulus-evoked beta and observed decreases over posterior sites while mind wandering during variants of detection tasks (Baird et al., 2014; Cunningham et al., 2000; Martel et al., 2019). Of note, Cunningham and colleagues (2000) also found a similar decrease in beta-alpha and beta-(alpha + theta) ratio during mind wandering, which they interpret as a more sensitive measure of alertness. Together, this decrease in stimulus-evoked parietal beta may reflect reduced alertness or attention to external stimuli as explained by the decoupling accounts of mind wandering (Handy and Kam, 2015; Smallwood and Schooler, 2015).

Studies that used internally oriented tasks converged on the same pattern, with all three studies examining beta reporting lower levels of frontal beta not time-locked to external stimulus during periods of mind wandering (Braboszcz and Delorme, 2011; van Son et al., 2019a, 2019b). Given that frontal beta activity has been implicated in preventing thoughts from coming to mind (Castiglione et al., 2019), which parallels its well-established role in motor inhibition (Verbruggen and Logan, 2009), these findings may reflect specific instances of disrupted cognitive control pertaining to the occurrence of spontaneous thoughts during mind wandering. Despite this consistent pattern of decreased beta not time locked to external stimulus observed during mind wandering however, one of these studies also reported the opposite pattern when beta was time-locked to a task-irrelevant tone (Braboszcz and Delorme, 2011). This particular reduction in stimulus-evoked beta may be accounted for by the decoupling accounts (Schooler et al., 2011; Smallwood and Schooler, 2015). Further work may clarify whether tonic frontal beta activity plays a functional role in the control of mind wandering.

Gamma. The two studies that examined gamma band activity used externally oriented tasks and only one of them found significant effects (Kirschner et al., 2012). These authors reported a simultaneous increase over right middle temporal cortex regardless of stimulus onset, interpreted as memory-related processes occurring during mind wandering, and stimulus-evoked decrease over occipital sites during mind wandering, which they interpret as disrupted control of goal-oriented attention (Kirschner et al., 2012).

4.3. An electrophysiological account of mind wandering

Thus far in this systematic review, we integrated findings of electrophysiological correlates of mind wandering. Here, we put forward an electrophysiological account of mind wandering that synthesizes the existing evidence in the field. We propose that electrophysiological activity in the brain serves to facilitate this fundamental cognitive phenomenon in two ways. First, during bouts of mind wandering, the electrophysiological response to stimuli in the external environment is dampened, enabling neurocognitive resources to be dedicated to internally oriented thoughts. Second, when mind wandering occurs, certain patterns of spectral activity emerge that potentially supports various aspects of this phenomenon. We elaborate on each tenet below.

The attenuation of the electrophysiological response to external stimuli helps facilitate mind wandering by disengaging neural resources from the external environment. This was observed mainly in ERP components, including the P1, N1 and P3, as well as selected spectral measures, such as theta and beta. This evidence is consistent with both the perceptual decoupling account that suggests perceptual processes are decoupled from mind wandering (Schooler et al., 2011; Smallwood and Schooler, 2015), as well as an extension of this account in which we proposed that this disengagement from the external world extends into later stages of information processing, therefore covering a broad array of cognitive functions beyond perception (Kam & Handy, 2013; Kam et al., 2015). Rested on the assumption that we operate with a single, limited pool of resources (Kahneman, 1973), each stream of input would compete for the same resources suggesting we can only attend to one stream at a time. Accordingly, when attention is oriented towards our ongoing thoughts during mind wandering, few if any resources remain for the external environment. This would explain the disruption of external processing during mind wandering, reflected in dampened electrophysiological responses to external stimuli. Our review of the literature suggests this decoupling effect is robust in ERP components. This is also observed in stimulus-locked theta and beta band activity in the few studies that examined these metrics; however, additional research is needed to verify the robustness of this effect. Although an attenuation of stimulus-evoked electrophysiological response during mind wandering offers insight as to how mind wandering is maintained in the presence of external stimuli, it does not inform the mechanisms that underlie the experience of mind wandering itself.

To that end, activity in several frequency bands may be important for supporting different aspects of mind wandering. The studies using breath focus or counting tasks are particularly informative in this case because of the absence of task-relevant external stimuli during the tasks, with their overall patterns of results being strikingly consistent. Studies using external tasks that did not examine stimulus-locked spectral measures can also be informative in revealing ongoing spectral activity related to mind wandering. While it would be difficult to establish whether a given spectral marker is an epiphenomenon or plays a mechanistic role, their presence during mind wandering can inform our understanding of the various aspects of this phenomenon. In particular, increased delta band activity during mind wandering may index reduced alertness, underscoring the role of delta in the arousal aspect of the phenomenon. That this pattern was not observed in some studies may suggest that mind wandering and reduced alertness need not be tightly linked, assuming methodological differences did not contribute to the discrepancies. In fact, one can imagine being completely absorbed and alert when mind wandering about an upcoming vacation; yet, the types of thoughts we more commonly have within an experimental context may be naturally less engaging given the contextual confines. In the theta band, increased theta activity and theta:beta ratio over fronto-central sites as well as coherence between distanced regions appear to represent the involvement of attentional control. Consistent with patterns observed in the fronto-parietal control network during internal attention via intracranial EEG recordings (Kam et al., 2019), these markers highlight the role of frontal theta in the attentional control aspect of mind wandering. Our recent review of studies using the lesion and intracranial EEG approaches led to a similar conclusion (Kam et al., 2022). Similar findings in frontal beta on its own and as part of the theta:beta ratio also implicates this measure in the control aspects of mind wandering. Finally, alpha band activity reflects mind wandering as a form of internally oriented attention. This is in line with theoretical accounts and empirical studies (Kam et al., 2018; 2021; Palva & Palva, 2011), and suggests alpha may be most directly related to the ongoing thoughts that occur when our attention is oriented internally during mind wandering. Accordingly, alpha band activity serves as a potential candidate for indexing the content or nature of such thoughts in future studies. Taken together, our brain appears to support mind wandering by dampening our electrophysiological response to external stimuli when they are present, and facilitates different aspects of this phenomenon through corresponding spectral features, including alertness, attentional control and the nature of our thoughts.

4.4. Limitations

Several limitations of this systematic review as well as the primary research included in this review should be considered. First, one of the key limitations is the substantial methodological discrepancies across the reviewed studies. To provide a cogent synthesis of their findings required some level of simplification, generalization and prioritization. Therefore, we only discussed factors that were relevant to most studies or that enabled us to categorize studies into large groups for comparisons. As an example, we discussed the extent to which the context in which mind wandering was assessed, different types of tasks, stimulus modality, and task relevance can account for inconsistencies in findings. However, beyond providing descriptive information (presented in Supplementary Figure 3 and Supplementary Table 4), we did not further examine a number of other methodological factors that may have also influenced the observed EEG patterns. These include sample size, frequency and total number of thought probes, trial numbers for each condition, as well as the amount of time preceding thought probes that were considered for the analysis.

Another limitation is the considerable variation in the EEG analysis approaches across the studies included in this review. Many factors reflect the degrees of freedom built-in to EEG analysis, which could have impacted EEG results as well as led to variability in findings: this includes decisions during preprocessing (e.g., filter settings, artifact rejection and correction, baseline duration, offline reference site), the type of measures (e.g., peak versus mean amplitude for ERP components, and power spectral density versus event-related spectral perturbation for spectral measures), time windows of analysis (e.g., broad categorization including stimulus-evoked versus non-stimulus-evoked intervals and finer comparisons reflecting differences on the order of milliseconds), the number of channels (e.g., the selection of electrodes based on own data or past studies versus all scalp locations; sensory versus source locations), definition of frequency bands (e.g., alpha band can be quantified based on canonical range from 8 to 12Hz up to 14Hz, or individual peak frequency), and analytic approach (e.g., a priori versus data driven, and univariate versus multivariate techniques). This diversity in analytic approach prevented us from systematically assessing their impact on the reported EEG findings. Similarly, given the heterogeneity in analysis choices (e.g., univariate versus multivariate analyses, mean/peak amplitude comparisons versus timepoint-by-timepoint analyses) and the different types of effect sizes reported (e.g. Cohen's d, Hedges' g, $\eta_p{}^2$, and $\eta_G{}^2$), it would have been difficult to implement a meta-analysis that could be meaningfully interpreted.

Finally, there is a range of quality across studies. We also opted to be as inclusive as possible by using multiple databases and including grey literature. The overall findings of our systematic review should be interpreted with this in mind. Notably, the heterogeneous methodological and analytic approaches observed is not unique to the field of mind wandering, nor is the presence of null or mixed findings. That certain trends emerged in light of this heterogeneity is a testament to the robustness of these markers. Nonetheless, these limitations need to be taken into consideration when interpreting our conclusions.

4.5. Future directions

The burgeoning literature on EEG investigations of mind wandering illuminate important future directions in both basic science and translational science. To date, the majority of findings examined the electrophysiological correlates of mind wandering occurrence, with minimal focus on the nature of mind wandering. Two exceptions include studies that revealed distinct EEG patterns of thoughts that dynamically flowed from topic to topic (Kam et al., 2021) as well as patterns associated with mind wandering with and without intention (Martel et al., 2019). As behavioral and functional neuroimaging studies begin to unravel the rich and diverse types of spontaneous cognition that occurs during mind wandering and the neural activation patterns they map onto, an important avenue for future basic science research is to investigate whether and how the heterogeneity of our ongoing thoughts correspond to dissociable electrophysiological patterns.

In parallel, establishing robust and consistent EEG markers of mind wandering will inform future translational science research that aims to predict the occurrence of mind wandering offline and eventually in real time (Dhindsa et al., 2019; Dong et al., 2021; Groot et al., 2021; Jin et al.,2020 , 2019; Kawashima and Kumano, 2017). A better understanding of which markers are the most robust and which markers emerge under a specific context will likely facilitate more accurate prediction. Further integration with other accessible measures such as eye tracking and physiological measures may also enhance prediction of mind wandering in the real world. Combined with machine learning tools, this avenue of research has important implications for educational, occupational, and clinical contexts in which control over attentional focus has impactful consequences.

4.6. Conclusion

The current systematic review aimed to provide a comprehensive overview of electrophysiological markers of mind wandering in healthy adults. Several consistent trends have emerged in this field. The most reliable EEG correlate of mind wandering is an attenuation in the amplitude of canonical sensory and cognitive ERP components. In support of the perceptual and sensory-motor decoupling accounts of mind wandering, these findings indicate that mind wandering involves the decoupling of attentional processes from the external environment. We also found that increased activity in the lower frequency bands spanning the delta, theta, and alpha range, as well as decreased activity in the beta band tend to reliably characterize periods of mind wandering. Future investigations are necessary to develop a deeper understanding of not only the correlates of mind wandering but also the mechanisms by which mind wandering occurs including the spontaneous occurrence of thoughts associated with this fundamental human phenomenon.

Data and Code Availability Statement

Data availability: all relevant data are reported in the manuscript and supplementary materials. Code availability: not applicable.

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