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Review

Local build-up of sleep pressure could trigger mind wandering: Evidence from sleep, circadian and mind wandering research

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ABSTRACT

Mind wandering (MW), or having thoughts unrelated to the task at hand, is a very pervasive phenomenon. Although research on MW has exponentially grown during the last decade and a half, the mechanisms behind this omnipresent phenomenon remain largely unknown. In this review, we will discuss some factors that have been shown to contribute to the occurrence of MW: the quality of sleep, the time of day when the task is performed, the chronotype of the individual and the duration of the task. The intriguing commonality between these specific factors is that they all suggest a relation between MW and sleep pressure. In line with recent work relating MW to local sleep-like activity, we here will argue that one of the mechanisms underlying the pervasiveness of MW might be the local build-up of homeostatic sleep pressure that inevitably occurs during task performance in the brain areas related to the task. Mind wandering could then occur not only to serve a biological purpose, e.g. brain protection, but also a functional one, e.g. off-line learning, that can be beneficial for behavioral performance.

1. Introduction

Some moments throughout the day are perceived as more optimal than others to perform a task. We typically do not choose to run a marathon or take an exam at the time that we normally go to sleep. Similarly, we prefer to complete a mentally challenging task when our mind feels refreshed and ready. Among other factors, performance crucially depends on the time of day [54,57], our circadian type (or chronotype; [8,9,51,60,76,102]), and on the quality of our sleep during the preceding night [1,41,48–50]. That is to say, these factors influence our ability to stay focused on a task while avoiding potential distractions or task unrelated thoughts. But even with optimal conditions, we often do recognize acute moments of mental fatigue during task performance (e.g. "I am tired of performing this task") that ultimately can lead to shifts on the focus of attention, away from the task at hand. This change of the focus of attention to task-unrelated or stimulus-independent thought is known as mind wandering (MW) [91]. Although recent proposals have highlighted the multidimensionality of the concept [78,80], the research described in this review operationalized MW according to this simple definition. Furthermore, all studies described here investigated MW with a method called experience sampling [34]. Experience sampling requires participants to report on their thoughts while completing a cognitive task. This collection of self-reports can be done in different ways, but the most frequently used is the probe-caught method in which participants are asked about their focus of attention at random or specific time points during the cognitive task [91]. Experience sampling is known to have its limitations [92,107], but more recent approaches using behavioural (e.g., reaction time variability; [6,32]) and physiological markers of MW (e.g. [18,28,31,67]) have been scarcely used in the context of the work presented here.

MW has been shown to be highly prevalent in daily life (from 20% to 50% of our time awake; [40,79], and this pervasiveness of MW is not without risk, given the mostly negative consequences it has on behavior. For instance, MW can hinder learning [97], is related to poor academic performance [86,101,105] and is a major predictor of liability in car accidents [26]. The detrimental effects of MW have also been detected across different cognitive tasks like sustained attention tasks, memory tasks and reading tasks (e.g. [6,14,16,25,32,62,64,74,84,88,94,96]).

Despite the exponential growth of MW research during the past fifteen years [92], it remains unclear what exactly causes MW episodes to occur. In this review, we will discuss some factors that have been shown to contribute to the occurrence of MW but that have not been investigated very thoroughly: the quality of sleep, the time of day when the task is performed, the chronotype of the individual and the duration of the task (i.e., the time-on-task). An interesting commonality between these specific factors is that they all suggest a relation between MW and sleep pressure. As will be discussed more in detail below, this suggestion nicely fits a recent proposal that related MW to local sleep in brain areas involved in task performance [3].

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1.1. MW is related to quality of sleep, time of day and chronotype

A few studies have suggested that *quality of sleep* influences MW. In one study, participants completed several forms sent via e-mail during eight days, including a trait-like questionnaire that measured overall MW tendencies, and a form on nightly sleep disturbances [56]. Results showed that the number of reported nightly sleep disturbances had predictive value for the amount of MW on the following day. Similarly, another study found that individuals who reported higher MW scores were also more likely to experience sleep disturbances [13]. This study was based on three surveys completed by 213 Chinese adults, and used a mediation analysis to demonstrate a bidirectional relation between MW and poor sleep quality. In one single experimentally controlled study, it was found that sleep-deprived individuals exhibited a greater amount of MW while performing a visual search task than individuals that experienced a regular sleeping night, although this effect was limited to participants performing a high-demanding version of the task [72]. While the studies investigating a direct relation between MW and homeostatic sleep drive are limited in number, highly similar results have been found for attentional lapses: the longer participants are deprived of sleep, the higher the number of attentional lapses (e.g., [20]). It could easily be argued that attentional lapses are not unlike MW episodes: both are - by definition - related to a temporary decrease in task-related attention with similar behavioral markers (i.e., an increase in behavioral variability; [20,33]). It could therefore provocatively be said that an attentional lapse is a MW episode without a registered phenomenological experience. Other indirect evidence might come from research on aging. The shallower build-up of sleep pressure while awake and a slower dissipation while sleeping [53,82] with increasing age might be related to the robust finding that healthy older adults report less MW episodes (for a review, see [52]).

In sum, an increase in homeostatic sleep pressure that accumulates during awake time, causes a decrease in the ability to maintain attention to a task and thereby increasing the occurrence of MW episodes. It has been shown, however, that the change in brain responses and behavioral performance caused by an increase in sleep pressure interacts with circadian rhythmicity [11,69], suggesting that the frequency of MW might also relate to the time of day and the individual's chronotype. Individuals are classified into chronotypes depending on their preferred time of day to do activities and sleeping preferences, in addition to other genetic [37] and physiological features [5,29,38,39]. Three chronotypes are generally considered: morning-, intermediate- and evening-type, although studies that relate chronotypes to behavior tend to focus on the extreme chronotypes (i.e., morning and evening chronotypes) only.

Evidence for a relation between MW and *time of day* has indirectly been demonstrated in a sustained-attention-to-response task (SART), a task widely used in MW research [54]. The SART is a Go/NoGo task in which a series of digits from 1 to 9 is presented to the participants [75]. Participants are instructed to press a key as soon as they see a number on the screen, but to withhold pressing in rare events, e.g. when the number 3 (i.e., a target trial) appears. Initially, correct performance in the SART should be easy, but participants must remain adequately attentive in order to refrain automatic impulses to respond when odd targets appear. However, failures in response inhibition are often detected and are typically interpreted as failures of sustained attention [55,75]. Furthermore, because failures in response inhibition have been related to MW episodes in the SART [14,15,85], they have been considered as a possible indirect index for MW. Manly and colleagues (2002) showed that the time of day did not influence the more automated or routine aspects of the task, but that it did influence response inhibition abilities. More specifically, the ability to inhibit a response to a target trial was lower in the early morning and late at night compared to early afternoon and evening. This result adds to other findings showing that responses that require a certain degree of control are more susceptible to the time-of-day effect than more automated or highly practiced responses [76], and suggests that MW occurs more when sleep pressure is relatively high.

In one study that investigated the effect of *chronotype* on sustained attention using the SART [46], response inhibition was found most effective when participants performed the task in their optimal testing state. This optimal state could be the morning or the evening depending on the chronotype of the individual, and influenced the ability to stay focused on the task and respond accordingly. It should, however, be noted that an analysis on the synchrony effect (i.e., the interaction between chronotype and time of day; [61] showed that the morning-type group was more accurate than the evening-type group at their respective optimal time of day. In detail, accuracy of morning chronotypes decreased linearly with time-on-task only in the evening session. In the evening chronotypes, the linear decrement was seen in the morning session, but also during the evening accuracy was attenuated. Similarly, another study investigated associations between chronotypes and the frequency of MW by means of self-report questionnaires at the inter-individual level. Consistent with these findings, more MW was found generally at the non-preferred time of day (i.e. evening for morning chronotypes, and morning for evening chronotypes), as well as a more pronounced negative correlation between MW and morning chronotypes [12].

The observation that the effect of time of day on MW is mainly observed in morning-types resonates with other studies showing that the differences in performance between chronotypes are particularly pronounced during the evening [22,77]. One possible explanation for why morning-types are more sensitive to the effect of time of day is that the kinetic build-up of sleep pressure is different between chronotypes, with a faster build-up in morning- than in evening-types [98]. Furthermore, in the morning-types the build-up of sleep pressure during daytime is amplified by the circadian sleep-promoting signals: When they perform a task in the morning, no sleep pressure has already been build-up during the day and this fits with their circadian wake-promoting signal. However, when morning-types perform a task in the evening, the accumulated build-up of sleep pressure during the day is now amplified by the circadian sleep-promoting signal, resulting in the worst time of day to perform a task. In contrast to morning-types, in evening-types these two processes (i.e., the build-up of sleep pressure during the day and the circadian signal) counteract and attenuate each other's effects [77].

1.2. The effect of time-on-task

Although the evidence discussed above illustrates how sleep-related factors influence the frequency of MW, even under optimal sleep-related conditions there are factors known to influence MW. Of particular interest in the current review is the effect of time-on-task: The longer you perform a task, the more likely it becomes that our thoughts drift away from the task at hand to task-unrelated thoughts [10,42,64,100]. The relation between MW and time-on-task, however, is mediated by the task demands. For example, Krimsky and colleagues (2017) showed that the frequency of MW increased more strongly for participants performing a high demanding visual recognition task compared to participants performing a low demanding version of the same task [42]. Other work showed that for more demanding tasks, the impact of MW on behavior increases with time-on-task. One study found that MW increased with time-on-task while performing a more and a less demanding version of the SART [64]. In both versions of the SART, MW increments were related to performance decrements, but MW was found to be more detrimental for performance during the more demanding standard SART. Similar results were obtained in another study where no overall relation between MW and performance was detected in a low demanding simple visual search task, but a strong relation between MW and performance was observed in a high demanding Eriksen Flanker task [100]. Interestingly, the mediating effect of task demands on the relation between MW and time-on-task is reminiscent of the effect of task demands on the relation between MW and sleep deprivation that was discussed earlier [72]. Also there, an increase in MW was mainly observed for sleep-deprived participants performing a high demanding task demands. As will be discussed more in detail below, these results might suggest that the nature of the MW episodes related to an increase in sleep pressure and those related to time-on-task might be very similar.

2. Why do we mind wander?

A few decades of research on MW has revealed different theoretical ideas about what causes the mind to wander. Although they differ in their details, the most prominent theories on MW all share the idea that MW occurs due to changes in the executive functions system. According to one account, task processing and MW *compete* for resources from the executive system, as MW itself consumes the same attentional resources that are needed for the primary task [83,91,92]. An alternative account claimed that MW is instead a consequence of a *failure* of the executive system to deal with interferences coming from internally continuous generated thoughts triggered by internal or external cues [63]. Here, the executive system features a proactive role to maintain resources dedicated to task demands, and a reactive role to suppress internal train of thoughts that could interfere with task performance. At the junction of these proposals, a more recent account suggests that MW indeed consumes executive resources, but that the negative behavioral consequences are related to executive control failures [99]. This account assumes that the attentional resources available for both task-related thought and MW are limited, and crucially, do not change over time. However, with time-on-task, the executive system fails to dedicate these resources to the task at hand. This failure of the executive system could also be motivated by the adaptation to the task or learning, which would ultimately result in less resources needed for task performance. In sum, executive control processes would decline over time leaving room for MW to overcome and hinder performance.

The change in the executive system is thought to cause a switch from task-related to spontaneous thoughts that are continuously generated by the default mode of brain activity [16,58,63,93]. The Default Mode Network (DMN) is a group of brain areas that were firstly identified as prominently active during resting state periods [27,73]and that later, were also implicated in the experience of MW [16,58,93]. It includes nodes such as the medial prefrontal cortex (mPFC), the parietal cingulate cortex (PCC), the precuneus, and both angular gyri [68,95]. In line with MW experience, the activity of the DMN was found to reflect brief lapses of attention [108], spontaneous, internally guided thoughts [2] and perceptually decoupled attention [93]. Interestingly, the DMN has been also related to dreaming during sleep. The overlap in the neural substrates of MW and dreaming led to the hypothesis that dreaming might be an intensified form of MW [19,24].

Evidence in support of the executive system being involved in MW comes from behavioral experiments showing that the frequency of MW is higher at the start of a low demanding task compared to a high demanding task [23,89,90]. Other work in favor of an executive account of MW comes from work relating an individual's working memory capacity to their frequency of MW. Here, however, the direction of the relation has been shown to be both negative [35], positive [47], or even absent in the case of a recent registered replication report [66]. Furthermore, other measures of the executive system such as metacognition and cognitive control, have also been shown to be unrelated to MW [21]. Other evidence for the involvement of the executive system was found in imaging experiments relating brain activity in the anterior cingulate cortex and the dorsolateral prefrontal cortex activity to MW [16,58,93], but also this finding is rather inconsistent (e.g., [45,96]).

3. The local depletion of resources

Because the weight of the executive system in theories on MW is very high in comparison with the empirical evidence for the executive system in MW, we here want to resuscitate another idea about the nature of MW, namely one based on resource depletion. The idea that MW is caused by a depletion of resources has previously been dispelled by arguing that MW itself requires the same attentional resources that are needed for the primary task [83,91,99]. However, by considering resource depletion as a local rather than a global phenomenon and by specifying this local resource depletion as a result of an increase in local sleep pressure (e.g., because of a need for cellular maintenance [103], or the necessity to remove potentially neurotoxic waste [109], we here argue that this idea should not be too readily discarded (see also [3]).

First, the effects of quality of sleep, time of day, and chronotype on MW, demonstrate a fascinating relation between sleep-pressure and MW: the more sleep-pressure, the more MW, especially for tasks that require many resources (i.e., high demanding tasks). *Second*, and essential for the current proposal, sleep pressure can be local. Wakefulness and sleep are not always discrete states, and can coexist at the same moment in different brain regions [17,30,43,44,71,81]. Recent work in sleep-deprived animals and epileptic human patients has demonstrated that parts of the brain can show sleep-like activity (i.e. slow wave activity and theta waves measured with electroencephalogram recordings) in the awake state [70,104], a phenomenon that is often referred to as *local sleep*. In detail, a study with rats showed that when the animals are kept awake for a long period, local neuronal populations are shortly going "offline" (i.e. transient periods of neuronal silence) like in sleep, albeit the animal is active and exhibits an "awake" EEG pattern [104]. Additionally, these offline neuronal periods are associated with slow/theta waves at the time impaired behavioral performance is observed. This study suggested that local sleep is use-dependent because it can be triggered by overloading task-related neuronal groups. Similar results were obtained in sleep-deprived epileptic patients, where single-neuron and local field potential activity recordings with intracranial electrodes showed that instances of local sleep precede cognitive lapses and were directly related to the presence of commission errors in a psychomotor vigilance task [70]. In healthy, sleep-deprived participants, extensive training on a specific task resulted in local sleep in the brain areas related to the task and a decrease in behavioral accuracy [7,30]. Combining the observation that sleep pressure has a positive relation with MW and the observation that sleep pressure can be local leads to the idea that MW could be related to the local depletion of resources: MW can be triggered by the local increase of sleep pressure evoked by overloading task-related areas.

Although there is yet no direct evidence for this hypothesis, partial support might already come from the observations described in this review. First, an overall increase in sleep pressure is related to an increase in MW but this is especially the case in high demanding tasks. We here suggest that this increase in MW is caused by local sleep pressure in the task-related brain. The local sleep pressure is caused by performing a demanding task and can be boosted by a homeostatic sleep pressure and the circadian pacemaker. Second, although the effect of time-on-task on MW can be explained by different theoretical accounts, the observation that this effect was stronger for high demanding tasks compared to low demanding task [42] fits nicely with the idea of local resource depletion. According to the local depletion account, the high load task depletes local resources more quickly and would therefore cause a sharper increase in the likelihood that participants will MW. Finally, in a recent study we tested whether changes in MW were related to global changes in the executive system or to a local build-up of sleep pressure due to task performance. Participants performed multiple sessions of a perceptual learning task that is known to evoke local changes in the visual cortex (i.e., the texture discrimination task; [36,65]). Results showed that an objective marker of MW (i.e. pupil phasic response) mirrored changes in task performance related to changes in visual processing rather than the changes in the executive system [33].

4. Conclusion

The evidence reviewed in the present article shows the scarce but interesting traces that relate different sources of sleep pressure build-up to MW. Studies show how a general need for sleep, caused by a lack of quality of sleep, the individual's chronotype, or the time of day at which a task is performed, increases the propensity to MW. Based on recent findings in sleep research, we here argued that this increase in sleep pressure could also act locally, i.e., in the brain areas related to performing a task. This local increase in sleep pressure (or this local depletion of resources, or local sleep; [3] causes the task-relevant areas to go "offline" and the brain to enter its default mode activity which is related to the phenomenological experience of MW. Although the evidence to support the idea of a local depletion of resources is limited, it provides an intriguing alternative explanation to the nature of MW episodes and could explain why MW is so pervasive. Future research relating local resource depletion to sleep-like brain responses during MW, e.g., increased cortical excitability and a breakdown of effective connectivity [59], could provide further evidence for our proposal. Local resource depletion could be installed by depleting specific cognitive functions (e.g., spatial working memory; [4]), or deteriorating perceptual responses (e.g., [65]).

It should be noted that given the numerous dimensions of MW [78], we do not propose that the local depletion of resources will account for all types of MW. Because the local depletion of resources is an inevitable, biological consequence of neural activity, it might provide an explanation of the nature of MW episodes that occur outside the intention of the individual, or those sometimes referred to as 'zoning out' or mind-blanking [80,87,106]. Intriguingly, the idea that MW occurs because of a local depletion of resources suggests that MW might serve a restorative function; it allows parts of the brain that are relevant for the task at hand to recover. Stretching this idea even further, it could even suggest that MW serves as brief offline learning episodes. This would lead to the prediction that, whereas previous work on MW has emphasized how behavior performance is worse during MW episodes, behavioral performance might in fact be better after MW episodes. Mind wandering would then occur not only to serve a biological purpose but also a functional one that positively affects behavioral performance.

CRediT authorship contribution statement

Esperanza Jubera-Garcia: Conceptualization, Writing - original draft, Writing - review & editing. **Wim Gevers:** Writing - review & editing. **Filip Van Opstal:** Conceptualization, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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