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Is mind wandering reflected in microsaccade dynamics?

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ABSTRACT

Mind wandering is a state in which our mental processes are directed towards task-unrelated thoughts. This phenomenon has been shown to underlie attentional lapses and represents a common experience in everyday life. Previous studies have found an association between mind wandering and eye-related indices. In the present study, we addressed for the first time whether the rate of microsaccades—miniaturised saccades that we spontaneously produce during prolonged fixation—is sensitive to the occurrence of mind wandering. Participants performed the Sustained Attention to Response Task, a go/no-go task highly vulnerable to mind wandering. The analyses focused on possible differences in microsaccade rate emerging from the comparison of time intervals preceding commission errors and time intervals preceding correct target withholds, under the assumption that a commission error would reflect a mind wandering episode. The results showed that microsaccadic rate was consistently reduced in time windows preceding a target trial in which participants produced a commission error as compared to when they correctly inhibited the tendency to manually respond. Cluster-based analyses established that this pattern was robust. Because microsaccades are known to occur involuntarily and a reduction in their frequency has been associated with higher mental effort, the present findings provide new insights as regards the relevance of mind wandering and lend support to the idea that during mind wandering our mind is far from being idle and is absorbed and committed to effortful activities instead.

1. Introduction

Mind Wandering (MW) is a condition where our mental focus deviates away from an ongoing task (for a review, see Smallwood & Schooler, 2015). MW is characterised by the production of self-generated, task-unrelated thoughts, that are automatically activated and typically involve personal matters, concerns, and plans about the future (e.g., Baird et al., 2011; Ottaviani et al., 2013). MW has been shown to occur and hamper performance in highly demanding cognitive activities such as text comprehension (e.g., Unsworth & McMillan, 2013), learning in online lectures (Szpunar et al., 2013), and driving (e.g., Yanko & Spalek, 2014). However, the perceptual decoupling process responsible for disengaging attention from the current task which gives rise to MW seems to be primarily triggered in relatively low-demanding, monotonous tasks (e.g., pressing a button when a visual stimulus appears repeatedly) that do not strongly engage executive control (e.g., Seli et al., 2018; Teasdale et al., 1995).

One big issue related to MW is concerned with its intrinsically *subjective* and *covert* nature. In lab-based studies, the occurrence of MW episodes is often monitored online by means of the so-called experience sampling method (for a review, see Weinstein, 2018), which consists of having participants performing a given task and suddenly interrupting them by presenting probes asking whether, at the current moment, their attentional focus is directed to the assigned task or 'off task' instead (i.e., engaged in MW). While the experience sampling method has turned out to be a useful procedure to assess MW (also outside the lab, see Varao-Sousa & Kingstone, 2019), it is obviously prone to the limitations that are known to characterise self-report measures, such as reliability and social desirability. For this reason, using a triangulation-based approach, researchers have attempted to combine subjective probe-caught measures with independent, objective measures of cognitive functioning at either the behavioural or neural level, to possibly detect similar modulations driven by MW episodes (Smallwood & Schooler, 2015). On the neuroscientific side, these efforts have led to the observation that MW is associated with lower amplitude components of event-related brain potentials known to reflect task-related attention, such as P3 (e.g., Smallwood et al., 2008). Critically, MW has also been associated with the involvement of both the default mode network

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(Mason et al., 2007) and the executive network (Christoff et al., 2009). This involvement, in turn, indicates that our brains are far from being 'silent' and 'lazy' during MW episodes and suggests that, during MW, our cognitive system is committed to effortful activities, although irrelevant for the task at hand.

Of particular relevance for the present study, ocular measures have also been investigated as potential *overt* proxies of MW episodes. In this regard, MW has been found to occur in association with increased pupil diameter (e.g., Franklin et al., 2013; Pelagatti et al., 2020), in line with the view according to which increased pupil dilation would index increased cognitive effort (e.g., Dalmaso et al., 2020; Lisi et al., 2015). Other studies, however, have reported different findings (e.g., Konishi et al., 2017; Unsworth & Robison, 2016). Different investigations focusing on oculomotor indices have provided evidence suggesting that MW is associated with longer fixation durations during reading (e.g., Foulsham et al., 2013; Reichle et al., 2010; but also see Uzzaman & Joordens, 2011) and real-world scene viewing (Krasich et al., 2018), although modulations of classic oculomotor parameters (e.g., fixation duration, fixation dispersion) seem to be contingent on the specific type of primary task (see Faber et al., 2020). Interestingly, there is also evidence indicating that MW would be associated with higher blinking frequency (Smilek et al., 2010; Stawarczyk et al., 2020; but also see Faber et al., 2018; Uzzaman & Joordens, 2011), a finding consistent with the occurrence of perceptual decoupling, attentional disengagement, and attenuated processing of the external input (e.g., Volkmann, 1986).

Here, we were interested in addressing whether microsaccades, a specific type of fixational eye movement, could also be sensitive to MW. These typically involuntary, miniaturised, and rapid eye movements, usually executed during prolonged fixation (see Rolfs, 2009, for a review), have been shown to be involved in different perceptual (e.g., Otero-Millan et al., 2012) and attention-related phenomena (e.g., Betta et al., 2007; Engbert & Kliegl, 2003). Most crucially, the absolute rate of microsaccades in response to external stimuli appears to be inversely related to task difficulty and mental effort. This has been demonstrated in studies using several types of tasks. For instance, Valsecchi et al. (2007) used a visual oddball task and showed that microsaccadic rate was lower in response to rare as compared to frequent targets, but only when participants were asked to actively process them (also see Valsecchi et al., 2009; Valsecchi & Turatto, 2007, 2009). Siegenthaler et al. (2014) employed arithmetic tasks varying in complexity and observed that when participants were asked to perform difficult tasks (backward counting) microsaccadic rate was lower than when they were asked to perform easy tasks (forward counting). Gao et al. (2015) observed similar results using different calculation tasks. A related pattern of findings has been later reported by Dalmaso et al. (2017), who used a working memory task in which participants had to memorise short vs. long numerical sequences and showed that microsaccadic rate during the retention period decreased as memory load increased (also see Krejtz et al., 2018, for similar results). Kadosh et al. (2024) have recently replicated these latter findings using a working memory task with stimuli varying in shape, colour, and location. Interestingly, they have also reported that participants' performance in the working memory task was enhanced when microsaccades were suppressed. They have interpreted this finding as suggesting that oculomotor inhibition may operate by silencing the visual input while processing current stimuli. Similar outcomes have been observed in acoustic tasks, such as in Lange et al. (2017), who reported that microsaccadic rate was inversely related to self-reported absorption in music listening.

In summary, fluctuations in microsaccade rate have been shown to reflect cognitive effort in different tasks, but no study, to the best of our knowledge, has attempted to assess whether the frequency of these tiny eye movements covaries with MW. Focusing on microsaccades is particularly interesting considering their typically involuntary nature (see Martinez-Conde et al., 2013), and hence they may represent a valid pipeline for addressing MW dynamics. In the context of MW, the inverse relationship between microsaccadic rate and subjective task difficulty/task engagement might be reflected in opposite predictions. On the one hand, one might expect microsaccadic rate to be higher during a MW episode as compared to an 'on-task' episode. This pattern would be in line with the idea that microsaccades index cognitive effort *specifically* devoted to the task at hand (see, e.g., Fried et al., 2014). On the other hand, one might expect the reversed pattern, based on the notion that MW episodes are associated with effortful (albeit irrelevant for the task at hand) processing often involving complex cognitive activity underlying self-generated thought. The important role of this cognitive activity is indicated by neuroimaging studies which demonstrated a positive correlation between MW and the involvement of complex brain networks such as the default mode network and the executive network (e.g., Christoff et al., 2009; Mason et al., 2007). This latter scenario would be consistent with the suggestion that the load-rate inverse relationship can also reflect abstract thinking (Lange et al., 2017).

In order to address these issues, we implemented a modified version of the Sustained Attention to Response Task (SART; Robertson et al., 1997), similar to that used by Stawarczyk et al. (2014) for assessing MW. We opted for SART because it is a monotonous vigilance task known to induce MW episodes (e.g., Martínez-Pérez et al., 2021) and it is less prone to individual differences with respect to other tasks such as reading (for instance, different participants may be either fascinated or bored during the reading of the same text passage; see, e.g., Hollander & Huette, 2022). The SART is based on a go/no-go task which requires withholding of manual responses to a rare target stimulus while responding to frequent non-target stimuli. Combined with the experience sampling method, this paradigm allows to assess the occurrence of MW episodes using an objective behavioural measure (i.e., errors in the primary task, which are interpreted as attentional lapses subtending MW; see, e.g., Seli, 2016; Smallwood et al., 2008; Stawarczyk et al., 2011, 2014), while also enable to explore subjective indices (i.e., probe-caught measures). Our analyses, aimed at detecting variations in microsaccade rates, were focused on the time interval immediately preceding the onset of the two critical stimuli used to assess MW: target stimuli in the SART and thought probes. More specifically, we looked at possible differences in microsaccade dynamics emerging from the comparison of time intervals preceding SART commission errors and time intervals preceding correct target withholds, under the assumption that a commission error likely results from a MW episode (e.g., Smallwood et al., 2008). In the same fashion, we compared microsaccade rates preceding thought probes as a function of the participants' self-report of their attention being directed to the assigned task or not.

2. Methods

2.1. Participants

We established an a priori target sample size of 50 participants based on previous studies aimed at investigating the impact of mental effort on microsaccades (e.g., $N = 30$ in Dalmaso et al., 2019; $N = 26$ in Kadosh et al., 2024; $N = 31$ in Lange et al., 2017; $N = 38$ in Salvi et al., 2020) and in line with studies addressing gaze allocation during MW (e.g., $N = 51$ in Krasich et al., 2018; $N = 33$ in Stawarczyk et al., 2020). Fifty-one naïve students (mean age = 24 years, $SD = 2.83$, 10 males) with normal or corrected-to-normal vision participated in the study. Data collection was stopped at the end of a booking session. The study was approved by the Ethics Committee for Psychological Research at the University of Padova and conducted in accordance with the guidelines laid down in the Declaration of Helsinki. Informed consent was obtained from all participants.

2.2. Apparatus

Eye movements were recorded binocularly at 500 Hz using an EyeLink 1000 Plus (SR Research Ltd., Ottawa, Canada). Stimuli were presented through Experiment Builder (SR Research Ltd., Ottawa, Canada), on a 24-in monitor (1280 × 1024 px, 120 Hz) placed 65 cm away from the participant. Head movements were prevented by a chinrest.

2.3. *Stimuli and procedure*

As anticipated earlier, the experimental paradigm relied on the combined use of both the SART and thought probes (see Fig. 1), similar to the procedure implemented by Stawarczyk et al. (2011; also see Christoff et al., 2009). The SART is a go/no-go task, characterised by the presentation of one digit extracted from the 0–9 range. Here, participants were instructed to respond using a mouse click with their dominant hand to the presentation of any digit (the non-target stimuli), except for the number 3 (i.e., the target stimulus). Thought probes were used to collect subjective MW reports during the SART. They consisted of two questions: the first one asked whether participants' attention was focused on the task or on task-unrelated thoughts; the second question asked whether participants were aware or not of where their attention was focused. In both questions, the participants could respond on a seven-point scale. For the first question, '1' indicated 'completely on task' and '7' indicated 'completely off task', whereas for the second question, '1' indicated 'completely aware' and '7' indicated 'completely unaware'.

The experiment started with a nine-point calibration, followed by a validation procedure. Next, 7 identical blocks were administered. The first block was composed of practice trials and was followed by the experimental blocks. Before each block, the participants were asked to fixate a centrally-placed cyan circle (0.4° diameter), and then the experimenter initiated the block through the host pc. This procedure ensured that participants were fixating on the centre of the screen and allowed to perform a drift checking. A successful drift checking was followed by an acoustic warning stimulus (1000 Hz) lasting 150 ms that signalled the imminent start of the block. Each block included 16 target trials (in which the number '3' was presented), 16 thought-probe trials (in which the two questions appeared instead of the numbers) and 297 non-target trials (in which non-target numbers were presented), for a total of 329 trials. All stimuli appeared centred on the screen, and each digit (0.5° × 1°) was accompanied by a superimposed, centrally-placed, cyan circle (i.e., the fixation spot). Digits appeared in black over a grey background. Target and thought probes were always separated by a variable number of trials in the 4–15 range. Trials in which digits were presented consisted of the onset of a single digit and a superimposed fixation spot for 250 ms. Afterwards, the digit disappeared, and the fixation spot remained on the screen for 1750 ms before the next trial started. Participants were instructed to look at the centre of the screen (i.e., on the fixation spot), to respond as fast as possible with the click of the mouse when a non-target digit was presented, and to withdraw from responding when the target digit (i.e., the '3' number) appeared. When a thought-probe occurred, participants were presented with the sequence of the two questions addressing subjective MW reports. Responses were provided by clicking the mouse over one of the seven buttons on the screen with no time limit (see Fig. 1). Thought probes stayed on the screen until a response was provided, thus participants could temporarily rest their eyes. Thought-probe trials were always followed by a non-target digit trial.

At the end of each block, the participants were invited to rest their eyes and they were asked to inform the experimenter when they were ready to start the next block. The participants were also instructed to avoid blinking during the experimental trials as much as possible. Overall, the experiment lasted about an hour and a half.

2.4. *Data analysis*

The first step in microsaccade analysis consisted of extracting all the eye position traces corresponding to the epochs preceding the presentation of the relevant stimulus (i.e., either the number '3' or the thought probes). In particular, we cut the traces starting 100-ms prior to the onset of the non-target stimulus preceding the relevant stimulus and terminating at the onset of the relevant stimulus. Subsequently, we identified binocular (micro)saccades using the algorithm proposed by Engbert and Kliegl (2003), as implemented in the Microsaccade Toolbox for R (Engbert et al., 2015). This algorithm identifies microsaccades as outliers in the velocity space in order to distinguish them from other classes of fixational eye movements. The duration and velocity parameters were set at 6 ms (minimum duration) and 5 standard deviations (velocity threshold). In order to evaluate the potential microsaccadic correlate of mind wandering, we used nonparametric cluster-based randomization tests (Maris & Oostenveld, 2007) to identify the possible presence of time intervals in which microsaccade rate might have differed as a function of the response to the subsequent target. Nonparametric cluster-based randomization tests allow for the identification of significant differences between two signals varying in time without the need to specify a priori time regions of interest for testing,

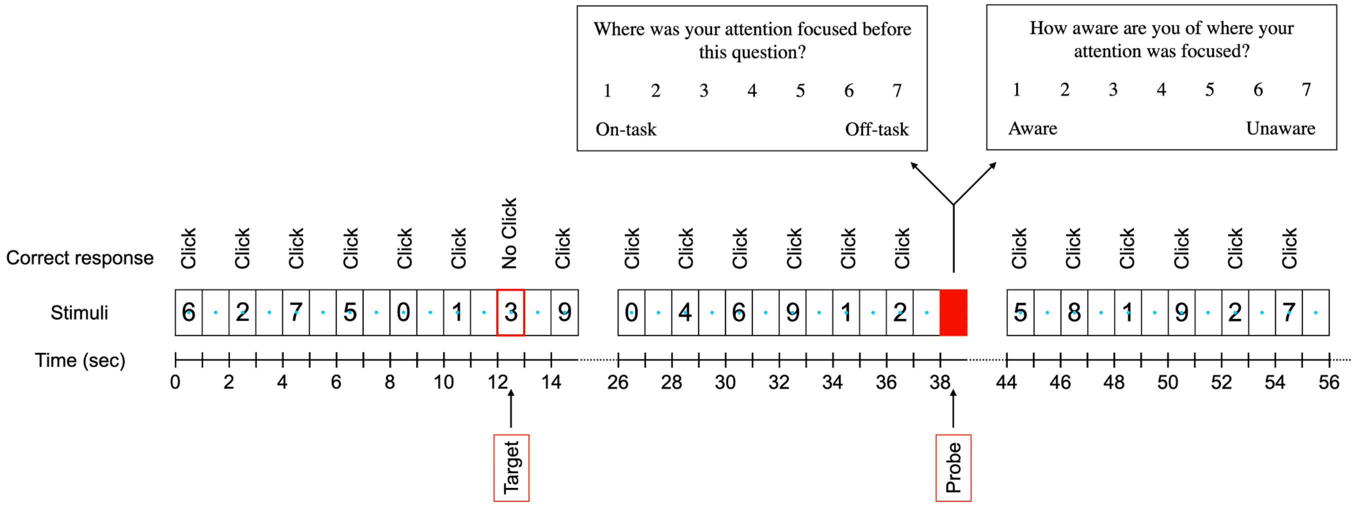

Fig. 1. Schematic illustration of the sequence of events during the experimental paradigm. Non-target stimuli in the SART (i.e., digits other than '3') required a manual response. Target stimuli (i.e., the digit '3') were rare and required participants to withhold the response. Number stimuli were created so that they had approximately the same size. Thought probes occurred unpredictably and consisted of two sequentially displayed questions addressing subjective MW reports. Time is expressed in seconds.

and this approach has already been applied to testing microsaccadic correlates in other domains (e.g., Widmann et al., 2014). We implemented cluster-based nonparametric randomization tests using paired-t as a test statistic, two-tailed $p < .05$ as the condition for identifying candidate clusters, and 10000 permutations to compute the Monte-Carlo cluster-level significance threshold.

3. Results

3.1. SART

Two participants were excluded from the analyses of the SART because they produced less than 10 commission errors, and therefore did not provide reliable measures for the evolution of microsaccade rate.

For the remaining 49 participants, the average error rate for target trials was 46.22 % (*SD* = 18.17). This conspicuous rate of commission errors enabled us to obtain a large set of observations for both correct and incorrect responses in the critical trials reflecting objective behavioural measures to assess MW episodes. The mean response time in correctly responded non-target trials was 361.25 ms (*SD* = 74.35).

3.2. Thought probes

Neutral ratings (i.e., '4' responses) were excluded from the analyses; ratings below 4 were counted as 'on task' and 'aware', whereas ratings above 4 were counted as 'off task' and 'unaware' (see Christoff et al., 2009). The average frequency of ratings for the two thought probe questions is illustrated in Fig. 2. On the first question ('on task' vs. 'off task') participants reported an average rating of 3.3 (*SD* = 1.3) and, on the second question ('aware' vs. 'unaware'), an average rating of 3 (*SD* = 1.2). On average, participants reported being 'on task and aware' in 66.3 % of the trials (*SD* = 29.2 %), 'off task and unaware' in 21.5 % of the trials (*SD* = 27.3 %), 'on task and unaware' in 3.5 % of the trials (*SD* = 6.3 %), and 'off task and aware' on 8.7 % of the trials (*SD* = 12 %). Given the scarcity of trials in which the responses to the two questions were conceptually dissociated (i.e., participants reporting that they were aware of being off task or unaware of being on task), for the analysis of microsaccadic rate we only contrasted the trials where respondents reported being 'aware and on task' (i.e., those in which MW was least likely) against the trials where they reported being 'unaware and off task' (i.e., those in which MW was most likely; see, e.g., Christoff et al., 2009). Given the large imbalance in the responses ('on task' + 'aware' was reported on average three times more often), we were forced to relax our minimum number of trial requirement so that only at least 5 trials for each condition were needed in order to include participants in the analysis (see next section). Yet, we were still able to include only 25 participants in the final sample.

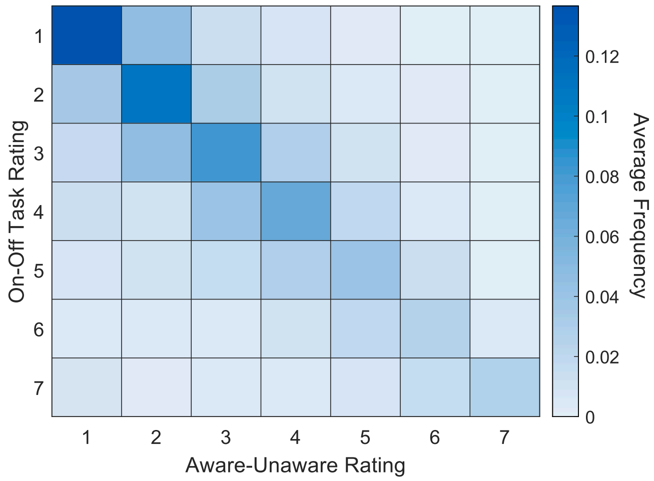

Fig. 2. Average frequency of ratings for the on-off task thought-probe question and for the aware-unaware probe question. The participants most frequently reported being both on task and aware. For completeness, the average frequency associated with 4 (the 'neutral' response) is also displayed, but these responses were excluded from the analyses.

3.3. Microsaccades

3.3.1. Microsaccade detection algorithm

We discarded from further analyses all microsaccades whose start fell in an interval starting 120 ms prior to the beginning of a blink and ending 120 ms after the end of the blink, to avoid potentially identifying artefactual eye signals related to eyelid closing as microsaccades (see Bonneh et al., 2015 for a similar approach). We further discarded saccades with amplitudes above 2° of visual angle. In the case of epochs time-locked to the onset of the target, this led to the removal of 540 saccades altogether from the 49 participants included in the analyses, leaving us with a total of 16082 microsaccades (see Fig. 3). In the case of epochs time-locked to the thought probes, this led to the removal of 234 saccades altogether from the 25 participants included in the analyses, leaving us with a total of 7816 microsaccades (see Fig. 3).

3.3.2. Microsaccade rate time-locked to target

After detecting microsaccades, we computed the raw microsaccade rate throughout the 2-s epoch leading up to target onset for each participant and type of response provided (i.e., correct withhold vs. commission error). This rate was computed as the number of microsaccades detected starting at each sample divided by the corresponding overall sampled time (2 ms for each averaged trial). In order to both visualising the evolution of the microsaccade rate and conducting cluster-based nonparametric permutation testing, the raw rates were smoothed with a Gaussian kernel with a standard deviation of 40 ms. It should be noted that trials in which participants failed to respond to the non-target stimulus preceding the target (8.73 % of trials, *SD* = 6.6) were excluded from further analyses (i.e., all epochs that were averaged included a keypress). This choice was motivated by the idea that missed responses to non-target stimuli were less likely to be associated with the occurrence of a MW episode. Moreover, missed responses to non-target stimuli may also activate processes other than those under investigation here (e.g., thoughts related to the just committed error).

The evolution of the microsaccade rate as a function of the response provided (correct withhold vs. commission error) in the epoch beginning with the onset of the non-target stimulus preceding the target and ending with the onset of the target is shown in Fig. 4 (correct withholds: 8637 microsaccades in 2361 epochs; commission errors: 6176 microsaccades in 1852 epochs). It is well known that the presentation of brief visual stimuli tends to produce a pattern of microsaccadic inhibition followed by a rebound, where the maximum inhibition tends to occur between 100 and 200 ms after the onset of the stimulus (e.g., Engbert & Kliegl, 2003; Galfano et al., 2004), at least for high-contrast stimuli (Bonneh et al., 2015), whereas the rebound might vary in amplitude and latency likely based on top-down influences which can generate a longer inhibition when the stimulus is detected (White & Rolfs, 2016) and is task-relevant (Valsecchi et al., 2007). The present results replicated this expected pattern, showing a peak inhibition centred approximately 150 ms after the onset of the non-target stimulus. However, the data also clearly showed a separate inhibition-rebound pattern following the first after approximately 250 ms. We speculate that this response might be induced by the termination of the stimulus, which followed the onset with a delay of 250 ms. This reasoning is based on the notion that an increase in luminance is not strictly necessary for inducing microsaccadic inhibition (Valsecchi & Turatto, 2007).

The nonparametric cluster-based analysis allowed us to identify two significant clusters with Monte-Carlo *p*-value lower than two-tailed .05, one between 454 and 718 ms ($p < .001$) and one between 1238 and 1454 ms ($p = .035$) after the onset of the non-target stimulus. In both

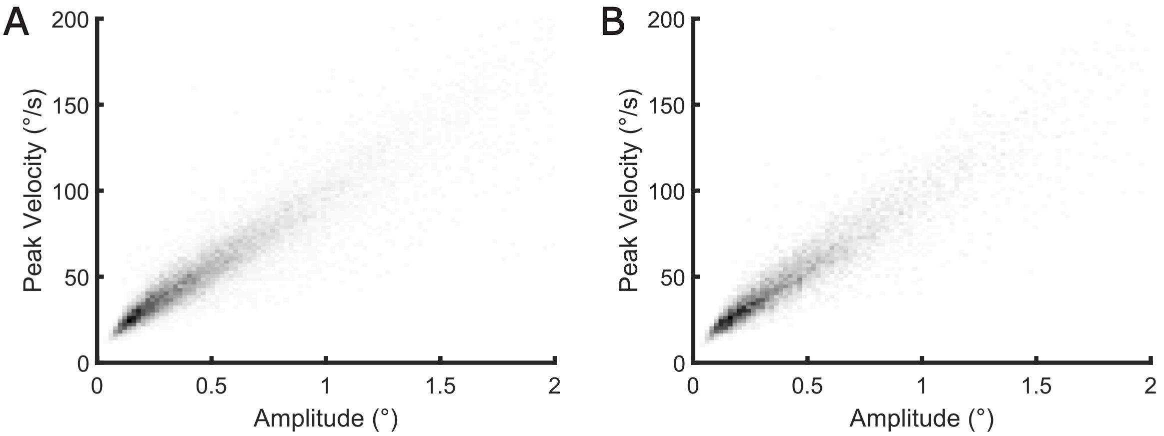

Fig. 3. Probability density plots of microsaccadic amplitudes as a function of microsaccadic duration from the epochs time-locked to the target (A) and the thought probes (B). As expected, the data from both datasets show a clear relationship between amplitude and peak velocity, namely the microsaccadic main sequence (Bahill et al., 1975; Engbert, 2006; Zuber et al., 1965). It is important to note that the vast majority of microsaccades had amplitudes below 0.5° and peak velocities below 50°/s.

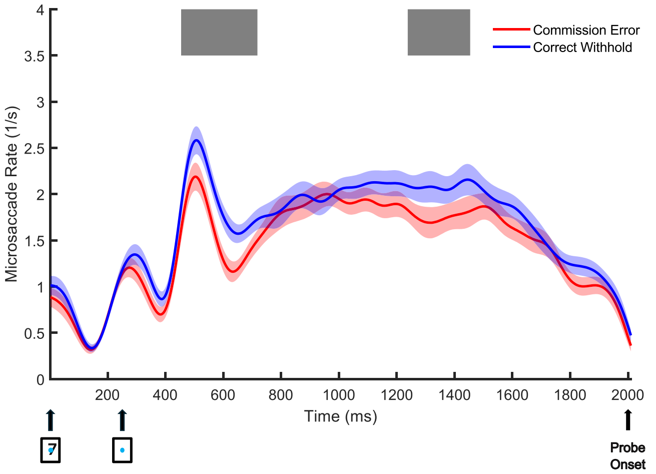

Fig. 4. Evolution of microsaccade rate over the course of the interval between the onset of the non-target stimulus preceding the target (here exemplified by the digit '7', which disappeared after 250 ms, leaving the fixation spot alone) and the onset of the target (the digit '3'), as a function of the accuracy of the response. The blue line represents the microsaccade rate for correctly withheld responses, whereas the red line represents the microsaccade rate for commission errors. The inhibition-rebound pattern induced by both the onset and termination of the stimulus and a final slow rebound phase is evident in both traces with similar time courses. The shaded areas represent within-participant 95 % confidence intervals computed at each time point following the algorithm introduced by Cousineau (2005). Among the sections of nonoverlapping confidence intervals, the nonparametric cluster-based analysis identified two clusters with a Monte Carlo p $<$ .05, which are indicated by the two gray bands above the microsaccade rate plots. In both clusters the data show evidence for an enhanced microsaccadic rate in epochs preceding correctly withheld responses as compared to commission errors.

clusters the microsaccadic rate was higher in epochs preceding correctly withheld responses as compared to epochs preceding commission errors. In order to illustrate the consistency of the effect across participants, in Fig. 5 we depict individual microsaccadic rates within the significant clusters.

3.3.3. *Microsaccade rate time-locked to thought probes*

The procedure for computing microsaccadic rate in the 2-second epoch leading up to the thought probes for the two types of responses ('on task and aware' vs. 'off task and unaware') was identical to the one we used in epochs time-locked to target onset. Similar to the analyses time-locked to target, we excluded from further analyses the trials in which participants failed to respond to the stimulus preceding the thought probes (i.e., all epochs that were averaged included a keypress).

The evolution of microsaccade rate as a function of the response type ('on task and aware' vs. 'off task and unaware') in the epoch beginning with the onset of the non-target stimulus preceding the thought probe and ending with the onset of first probe question is presented in Fig. 6 ('on task and aware': 2996 microsaccades in 827 epochs; 'off task and unaware': 1620 microsaccades in 499 epochs). The present results replicate the finding of a double dip in microsaccade rate after the onset of the non-target stimulus as emerged in the analyses time-locked to target onset.

We applied the same nonparametric cluster-based randomization testing approach to identify possible sections of the microsaccadic response where microsaccadic rate would differ based on the responses to the subsequent thought-probe questions. In this case, the procedure did not produce any significant cluster with a two-tailed Monte Carlo $p < .05$.

This might indicate that, as concerns microsaccadic response, thought probes were not as diagnostic in assessing MW episodes as attentional lapses indexed by commission errors to target stimuli. However, most likely, the emerged pattern might simply reflect that excluding approximately half participants from the original sample, and the lower number of microsaccades, largely weakened the statistical reliability of the results. This hypothesis is also supported by the fact that the confidence intervals in Fig. 6 do show some separation around the second peak rebound of microsaccade rate, approximately corresponding to the first cluster identified in the target-linked analysis in Fig. 4.

4. Discussion

In this study, we examined whether MW could be mirrored in microsaccade dynamics. To this end, we used an experimental paradigm combining an experience sampling method with the SART and collected both objective and subjective correlates of MW episodes (see, e.g., Christoff et al., 2009; Stawarczyk et al., 2011). We addressed microsaccades because these fixational eye movements typically occur spontaneously and are known to be sensitive to task difficulty and mental effort (e.g., Dalmaso et al., 2017; Kadosh et al., 2024; Valsecchi et al., 2007), and can reflect task commitment (Contadini-Wright et al., 2023; Lange et al., 2017). Our analyses were focused on fluctuations in absolute microsaccade rate in the time window preceding the two critical measures used to uncover MW episodes, namely, responses to target

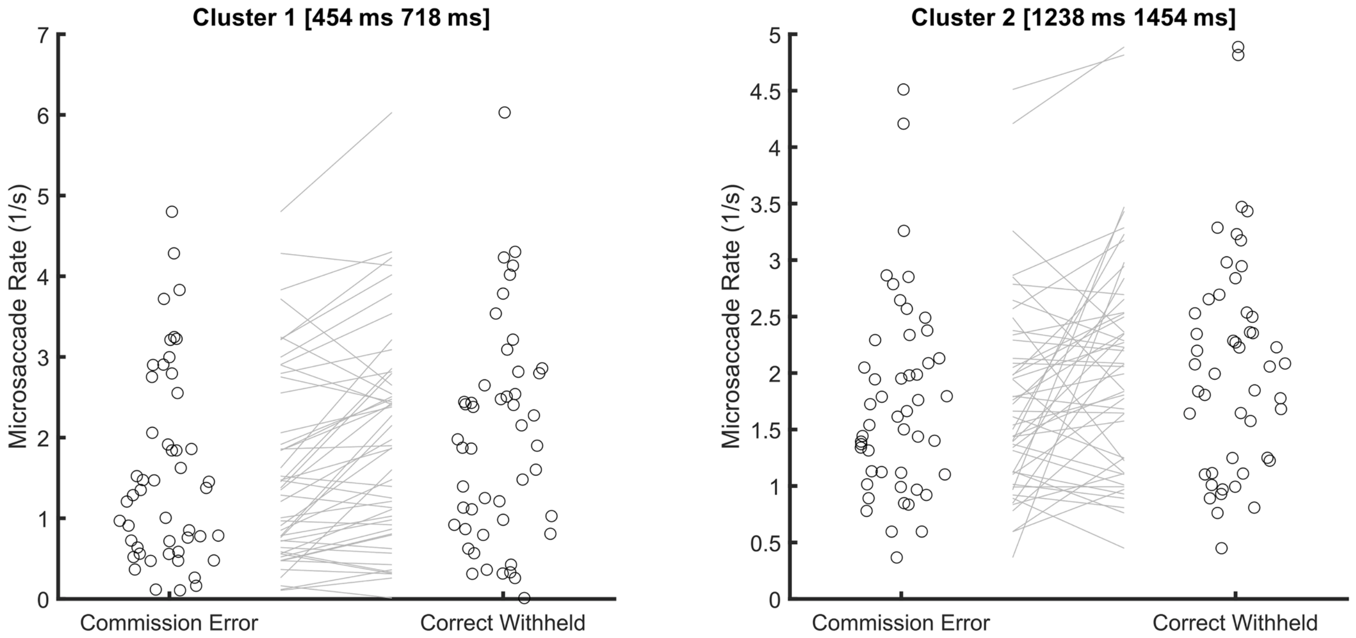

Fig. 5. Microsaccade rates within the first (left) and second (right) clusters identified by the nonparametric cluster-based randomization test for epochs preceding commission errors and correct withheld responses. Each circle represents the average for a single participant and each line represents a single participant's effect.

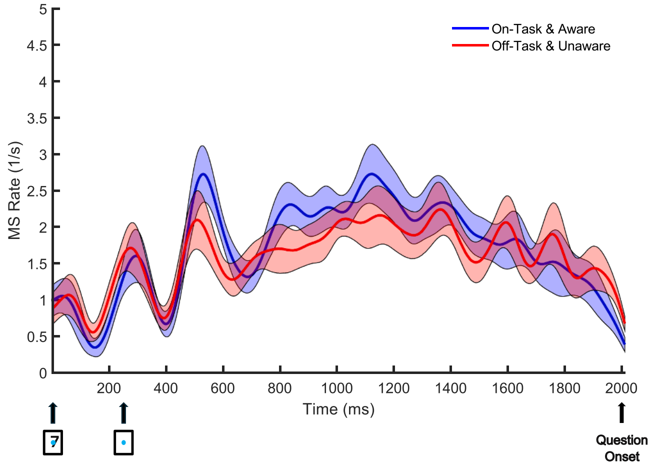

Fig. 6. Evolution of microsaccade rate over the course of the time interval between the onset of the non-target stimuli preceding the thought-probe questions (here exemplified by the digit '7'), which disappeared after 250 ms, and the onset of the first thought-probe question, as a function of the combined probe response. The shaded areas represent within-participants 95 % confidence intervals computed at each time point following the algorithm introduced by Cousineau (2005). The nonparametric cluster-based randomization test did not identify any cluster where the microsacaade rate significantly differed between epochs preceding probes to which participants reported being on task and aware, and epochs preceding off task and unaware responses (i.e. the data do not show evidence for a correlation between microsaccade rate and thought-probe responses).

stimuli in the SART and thought probes. Building on this, the analyses conducted on thought probes, comparing microsaccade frequency preceding MW self-reports vs. on-task self-reports did not reveal any substantial evidence for a difference, possibly due to the relatively low number of available data points. This issue will be further discussed later. In sharp contrast, the analyses conducted on SART targets, comparing microsaccade frequency preceding commission errors vs. correct response withholds, revealed a clear and robust pattern characterised by differences in the number of microsaccades executed in the time window prior to a correct non-response and prior to a wrong key-press. Interestingly, this dissociation in microsaccade rate started around 1500 ms before the onset of the target stimulus. In line with our theoretical framework, this time-course suggests a link with MW-related activity associated with an attentional lapse, which is known to underlie SART commission errors (e.g., Seli, 2016; Smallwood et al., 2008). Importantly, the direction of the effect was fully consistent with the load-rate inverse relationship (i.e., higher load-lower rate, and vice-versa) typically observed in tasks addressing microsaccade rate as a function of task difficulty (e.g., Dalmaso et al., 2017; Kadosh et al., 2024; Siegenthaler et al., 2014) or task commitment and absorption (Contadini-Wright et al., 2023; Lange et al., 2017).

It could be argued that this pattern could be accounted for by considering that the two conditions compared in the analyses (i.e., correct response withholds and commission errors), besides indexing different task accuracy, also differ in terms of motor preparation processes. Indeed, in the case of commission errors, participants executed a manual response, whereas in the case of correct response withholds no motor response was produced. In this regard, it is worth noting that Betta and Turatto (2006) reported an experiment in which they measured microsaccade rate when participants were instructed to manually respond to (active condition) vs. ignore (passive condition) stimuli. Their results showed that participants executed significantly fewer microsaccades prior to a stimulus in the active than in the passive condition. Thus, one may be tempted to conclude that the modulation emerged in the present study simply reflected differences in motor preparation and execution processes. We believe this alternative hypothesis can be rejected based on at least two different arguments. First, findings reported by Betta and Turatto (2006) were grounded on a very different experimental paradigm, in which active and passive conditions were presented in separate blocks. Conversely, in the present study, the participants had no cues to anticipate whether they were to press the response key or withhold response in the next trial. Second, and most critical, the dissociation in microsaccade rate between active and passive conditions in Betta and Turatto's experiment only started around 750 ms before the onset of the stimulus, namely in close temporal proximity with response execution, if any. In contrast, in the present study, the increase in microsaccadic rate for subsequent correctly withhold responses was present (and solid) already 1500 ms prior to target onset (see Fig. 4). For these reasons, we discard the alternative hypothesis based on motor preparation and are more inclined to interpret the observed pattern as reflecting a MW episode. This view converges with neuroimaging findings showing that MW is associated with persistent activity in complex brain networks such as the default mode network and the executive network—which include several cortical regions such as the medial prefrontal cortex, posterior cingulate cortex, dorsolateral prefrontal cortex, and anterior cingulate cortex (Christoff et al., 2009; Mason et al., 2007)—and suggests that our mind is involved in complex cognitive processing during MW episodes (also see Schad et al., 2024). Interestingly, microsaccades are believed to originate in the superior colliculus, a midbrain structure crucial for oculomotor control, and are modulated by inputs from the frontal eye fields, a cortical region located in dorsolateral prefrontal cortex involved in attentional regulation and executive control (e.g., Krauzlis et al., 2017; Peel et al., 2016). This interaction between subcortical and cortical areas may help explain the observed link between microsaccades and MW.

It is worth noting that in studies addressing microsaccade rate variations as a function of task difficulty, the inverse relationship between microsaccadic rate and mental effort was mostly phasic, in that it was apparently confined to a specific time window. For instance, Dalmaso et al. (2017) reported a modulation in a limited time interval during the retention phase of a working memory test. In a different study, Dalmaso et al. (2019) observed a similar pattern when participants were provided with cue stimuli that informed them about an upcoming cognitive conflict in a flanker interference task. Recently, using a speech-in-noise task with high and low listening load conditions, Contadini-Wright et al. (2023) have shown that not only microsaccadic rate was affected by listening load, but also that this modulation was localised in time, in that it specifically occurred during periods when demands on auditory attention were at their maximum. Intriguingly, in the present study, the time course of the modulation was rather different: the dissociation in microsaccade frequency preceding commission errors vs. correct response withholds was seemingly sustained over time in that it was visible in two successive clusters. This feature is more in line with phenomena characterised by relatively prolonged temporal extension such as MW (Pelagatti et al., 2020) than with other processes such as motor preparation or cognitive operations such as shifts of spatial attention (e.g., Betta et al., 2007; Engbert & Kliegl, 2003).

As concerns the direction of the observed modulation, to the extent that inhibition or suppression of microsaccades reflects increased mental effort (e.g., Dalmaso et al., 2017; Kadosh et al., 2024), our data are in line with a resource competition perspective, in which the deployment of cognitive resources for thoughts entailed in MW episodes would necessarily imply that fewer resources are available for processing external task-relevant stimuli (e.g., Smallwood, 2010). This would resemble a highly demanding dual-task condition, whereas ‘on task’ states may be more similar to single task scenarios in which the available resources are more focused on task-relevant external stimuli. The results are also consistent with the view according to which the same domain-general processes involved in handling stimuli belonging to the external environment would also be involved in insulating MW episodes from external stimuli by ensuring continuity and integrity of task-unrelated thoughts (Smallwood, 2013). Insulation, in turn, would shield MW against distraction from external stimuli, under the assumption that MW may serve important functions such as planning and anticipating personally-relevant prospective goals (e.g., Baird et al., 2011).

One notable aspect of the present study is that the pattern of microsaccade inhibition/suppression emerged in the analyses time-locked to target onset could not be properly addressed in the analyses time-locked to thought probes. Although self-report measures are popular tools for assessing MW, which have favoured important steps forward for better understanding this phenomenon (e.g., Weinstein, 2018), they are inevitably subjected to a loss of valid trials (e.g., neutral ratings) that, in turn, results in a reduction of data points that adds to other well-known factors such as social desirability. This is why we should be extremely cautious in drawing firm conclusions based on the null effect that emerged in our data. Future studies will be tasked with attempting to both increase the strength of the assessment of subjective experiences and replicate the present results using different cognitive paradigms suited to elicit MW episodes and detect microsaccades.

In conclusion, the present findings provide novel evidence showing a significant inverse relationship between MW episodes as inferred from commission errors in SART and microsaccade frequency. Because microsaccade inhibition is known to resonate with mental effort (e.g., Dalmaso et al., 2017; Kadosh et al., 2024; Siegenthaler et al., 2014), this pattern casts evidence that MW involves resource-demanding mental operations, in line with previous studies which monitored different eye-related activities such as blinking (e.g., Smilek et al., 2010).

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CRediT authorship contribution statement

Matteo Valsecchi: Visualization, Software, Investigation, Conceptualization, Writing – original draft, Supervision, Methodology, Data curation, Writing – review & editing, Validation, Resources, Formal analysis. **Eleonora Baldini:** Writing – original draft, Project administration, Data curation, Writing – review & editing, Validation, Investigation, Visualization, Methodology, Conceptualization. **Giovanni Galfano:** Writing – original draft, Supervision, Methodology, Formal analysis, Writing – review & editing, Validation, Resources, Funding acquisition, Visualization, Software, Investigation, Conceptualization. **Mario Dalmaso:** Writing – original draft, Supervision, Project administration, Funding acquisition, Conceptualization, Writing – review & editing, Validation, Resources, Investigation, Data curation, Visualization, Software, Methodology, Formal analysis. **Luigi Castelli:** Writing – original draft, Supervision, Methodology, Data curation, Writing – review & editing, Validation, Resources, Formal analysis, Visualization, Software, Investigation, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

This is to certify that neither generative AI nor AI-assisted tools have been used to create or alter figures, images and artwork in the present manuscript.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Mario Dalmaso reports financial support was provided by Italian Ministry of University and Research. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data associated with this work can be found here: https://doi.org/10.5281/zenodo.14391156

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