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# vmPFC damage reduces mind-wandering, but not other classes of off-task thought

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ABSTRACT

Ventromedial prefrontal cortex (vmPFC) is consistently engaged during mind-wandering, but its role in mind-wandering is still unclear. The present study tests the hypothesis that vmPFC is necessary for the (endogenous) generation of stimulus-independent and task-unrelated thought (mind-wandering), but not for externally triggered forms of off-task thought. To this aim, we studied off-task thought in vmPFC patients and brain-damaged and healthy controls, sampling the occurrence of different off-task experiences during a vigilance task, including mind-wandering, external distractions, and task-related thoughts. Moreover, we experimentally manipulated the presence of task-irrelevant cue-words capable to elicit mind-wandering (Standard condition vs. Cued condition). vmPFC patients showed reduced endogenously generated mind-wandering compared to the control groups (Standard condition), but also a weakened tendency to experience mind-wandering in response to cue-words (Cued condition). By contrast, vmPFC patients normally reported on (hence could become aware of) other types of off-task mental content, such as external distractions and task-related thoughts. These findings indicate that vmPFC integrity is necessary for the generation of mind-wandering, be this driven endogenously or by (minimal) cues, possibly by initiating the mental construction of personal (past and future) events that typically fuel mind-wandering. Without such internally generated content, attention is less likely to shift inward.

## 1. Introduction

The human mind has a marked propensity to decouple from the external environment and current goals and orient itself towards inner contents, such as memories, plans, and current concerns, a phenomenon known as mind-wandering (Antrobus et al., 1966; Smallwood and Schooler, 2006, 2015). The most paradigmatic form of mind-wandering is both stimulus-independent (generated endogenously) and task-unrelated (unrelated to the ongoing task or activity; Stawarczyk et al., 2011). An example is fantasizing about attending a future concert while driving. However, off-task thoughts can also be triggered by external stimuli (external distractions; e.g., "was that a thunder?"), or be related to (though not useful for) the ongoing activity (task-related thoughts; e.g., "driving is boring"). Recent theories define mind-wandering focusing less on the content of thoughts, emphasizing instead their dynamics, that is, how trains of thoughts unfold over time (Christoff et al., 2016; Zamani et al., 2022). A train of thought can be constrained deliberately (i.e., thinking actively to relevant information), automatically (i.e., driven by salient information) or freely moving (spontaneous), when both deliberate and automatic constraints are weak. It is in this latter case that the mind wanders: when it has no over-arching purpose, or imposed direction.

One important question pertains to the neural bases of our ability to generate thoughts abstracted from direct experience. Functional neuroimaging (fMRI) has linked mind-wandering with activity in the 'default mode network' (DMN), a set of interconnected brain regions, including the medial temporal lobe (MTL), ventromedial prefrontal cortex (vmPFC), posterior cingulate cortex, and the angular gyrus bilaterally, whose activity is enhanced during internally directed mental processes (Christoff et al., 2009, 2016; Fox et al., 2015; Kam et al., 2022). The DMN is generally more engaged during mind-wandering compared to other types of off-task experience that are less removed

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from perceptual reality, such as external distractions and task-related thoughts, though different subregions of the DMN respond preferentially to different forms of off-task experience (Stawarczyk et al., 2011; Kam et al., 2021; Smallwood et al., 2021). What is currently unclear is the precise functional contribution of DMN regions to mind-wandering. Studying mind-wandering in patients with focal brain damage can provide unique information about its cognitive and neural substrates, constraining the interpretation of the function of target brain regions.

Here we focus on the vmPFC. vmPFC is a node of the MTL subsystem of the DMN (Andrews-Hanna et al., 2010a) and is consistently active during mind-wandering (Mason et al., 2007; Smallwood et al., 2012; Fox et al., 2015; Stawarczyk et al., 2011). The thickness of medial prefrontal cortex regions is positively related to individuals' tendency to mind-wander (Bernhardt et al., 2014). More recently, using multi-dimensional experience sampling in conjunction with fMRI, Konu et al. (2020) found that vmPFC was the only region of the brain related to self-generated off-task thought, while the dorsal parietal cortex was associated with being on task (Turnbull et al., 2019). In addition, damage to vmPFC impairs the mental construction of personal past, future, and atemporal experiences, which typically populate mind-wandering events, suggesting that vmPFC damage should reduce mind-wandering as well (Bertossi et al., 2016a, 2016b, 2017a; De Luca et al., 2018).

This hypothesis was tested by Bertossi and Ciaramelli (2016), who assessed mind-wandering in vmPFC patients and brain-damaged and healthy controls while they performed various tasks varying in difficulty. vmPFC patients showed a reduced frequency of mind-wandering across tasks. Moreover, unlike the controls, their off-task thoughts were never about the future, and mostly present-oriented. Two recent studies confirm that inhibiting mPFC activity with transcranial direct current stimulation (tDCS) attenuates mind-wandering (Bertossi et al., 2017b; Giacometti Giordani et al., 2023). Interestingly, McCormick et al. (2018b) found a normal frequency of mind-wandering in patients with lesions to the MTL. MTL damage, however, altered the quality of mind-wandering, which was context-poor and semanticized in MTL patients compared to healthy controls. The finding that vmPFC damage precludes the experience of mind-wandering, whereas MTL damage just constraints its content, led us to propose that vmPFC (but not the MTL) is necessary for the endogenous initiation of mind-wandering, whereas the MTL would fuel mind-wandering with context-rich events (McCormick et al., 2018a; Ciaramelli and Treves, 2019; Ciaramelli et al., 2019).

An alternative possibility, however, is that vmPFC is not directly involved in the generation of mind-wandering, but in becoming aware of mind-wandering (Smallwood and Schooler, 2015; Faber and Mills, 2018). Drawing on Schooler's (2002) distinction, to realize that one is mind-wandering, for example while driving, one needs both awareness of the contents of one's thoughts (i.e., thoughts unrelated to driving) and "meta-awareness" that one is having that experience. This is the case when we catch ourselves thinking about an upcoming concert while driving. Awareness and meta-awareness can, however, dissociate. Sometimes we only realize after we get home that our mind wandered the entire drive, that we were thinking about the concert without even noticing the road (no meta-awareness). At other times we become aware in the moment that our mind has wandered, yet the specific contents of our thoughts elude us (no awareness of mental content). On this view, vmPFC patients may fail to report mind-wandering due to a lack of awareness of mental content or to a lack of meta-awareness.

The aim of this study was to test the hypothesis that vmPFC is necessary to enable the endogenous initiation of mind-wandering (McCormick et al., 2018a; Ciaramelli and Treves, 2019), studying self-generated and externally triggered forms of off-task experience in vmPFC patients. To this aim, vmPFC patients and brain-lesioned and healthy controls underwent a vigilance task requiring to distinguish (infrequent) patterns of vertical segments from patterns of horizontal segments while we assessed mind-wandering with thought probes. Critically, different from previous work (Bertossi and Ciaramelli, 2016), we probed participants to report separately on different types of off-task experience, including stimulus-independent and task-unrelated thought (mind-wandering) as well as off-task experiences triggered by external stimuli (external distractions) or the ongoing activity (task-related thoughts; Stawarczyk et al., 2011). If vmPFC is implicated in generating mind-wandering, rather than in becoming aware of the contents of one's thoughts, vmPFC patients should show reduced mind-wandering but remain capable of reporting externally cued off-task experiences, including external distractions and task-related thoughts. Moreover, we experimentally manipulated the presence of irrelevant verbal cues for mind-wandering, by testing participants in a Standard condition and in a Cued condition. In the Standard condition participants only saw the patterns of segments for the vigilance task. In the Cued condition during the vigilance task cue-words occasionally appeared on the screen, which have proven capable to trigger autobiographical memory retrieval and mind-wandering in healthy individuals (Schlagman and Kvavilashvili, 2008; Vannucci et al., 2014, 2017; Maillet et al., 2017). If vmPFC supports endogenously generated but not externally triggered mind-wandering, vmPFC patients should be impaired in generating mind-wandering endogenously in the Standard condition but not in response to cue words in the Cued condition.

A final question pertains to the temporality of mind-wandering. Bertossi and Ciaramelli (2016) found a selective reduction of future-oriented mind-wandering in vmPFC patients, consistent with the role of vmPFC in future-oriented cognition (Schacter et al., 2012; Stawarczyk and D'Argembeau, 2015; Ciaramelli et al., 2021a, 2021b). However, a tDCS study by the same group did not show a selective role of mPFC in future-oriented mind-wandering (Bertossi et al., 2017b). One problem of most previous studies is that they did not distinguish mind-wandering from other types of off-task experience, such as external distractions and task-related thoughts, which are typically present-oriented, which may dilute the relation between vmPFC damage and the temporal focus of mind-wandering. Therefore, here we re-examine the temporality of mind-wandering, with the prediction that vmPFC damage would especially hinder future-based mind-wandering (as in Bertossi and Ciaramelli, 2016).

## 2. Materials and methods

### 2.1. Participants

Participants included 23 patients with brain damage and 19 healthy individuals (see Table 1 for clinical data). Patients were recruited at the Centre for studies and research in Cognitive Neuroscience of the University of Bologna based on their lesion site (see below), as documented by magnetic resonance imaging (MRI) or computerized tomography (CT) scans. Nine patients had lesions involving the ventromedial prefrontal cortex (vmPFC patients, 3 females, mean age = 58.78 years, SD = 7.21; mean years of education = 10.33, SD = 2.78; see Table 1). vmPFC patients' lesions resulted from rupture of an aneurysm of the anterior communicating artery in eight cases, and in a brain tumor in one case, and were bilateral in eight cases and in the right hemisphere in one case. The remaining 14 patients had brain lesions that did not involve vmPFC (control patients, 3 females, mean age = 53.36 years; SD = 14.11; mean years of education = 11.43, SD = 3.65). Control patients' lesions were caused by ischemic or hemorrhagic stroke or brain tumor,

**Table 1**
Participants' neuropsychological profile (median and interquartile range).

| | RSM | DS | DSB | Prose recall | TMT (B-A) | Stroop errors | Stroop RTs |
|---|---|---|---|---|---|---|---|
| vmPFC patients | 32.50 (4.50) | 5.50 (1.00) | 4.00 (2.08) | 12.50 (10.10) | 60.93 (63.00) | 1.25 (2.50) | 21.00 (16.74) |
| Control patients | 25.88 (10.63) | 5.50 (1.18) | 3.27 (1.61) | 13.25 (5.87) | 113.50 (169.40) | 0.75 (2.25) | 21.45 (13.25) |
| Healthy controls | 30.25 (10.00) | 6.00 (1.62) | 4.28 (0.95) | 13.50 (4.00) | 24.99 (23.39) | 0.00 (1.62) | 17.46 (9.27) |

Note. vmPFC = ventromedial prefrontal cortex; RSM = Raven Standard Matrices; DS = digit span; DSB = digit span backwards; TMT (B-A) = Trail Making Test, difference in response times (RTs) between the B and the A forms (in seconds). We report corrected scores.

and were in the left hemisphere in 5 cases, in the right hemisphere in 7 cases, and bilateral in 2 cases. Lesion sites mainly included the occipital cortex (9 cases), the temporal cortex (9 cases), the parietal cortex (5 cases), and the dorsal frontal cortex (2 cases). For three of the fourteen control patients the lesion description was available but MRI scans were not, and therefore we could not reconstruct precisely the extension of the lesion (excluding these patients from the analyses did not alter the results meaningfully; see Tables 1 and 2 of the Supplementary material). There was no significant difference in lesion volume between vmPFC patients and the remaining eleven control patients (vmPFC patients M = 50.63 cc; SD = 31.22 cc; control patients M = 33.91 cc, SD = 26.20 cc, $t_{18} = 1.30$, p = 0.21). Included patients were in the stable phase of recovery (at least 3 months post-morbid) and had normal or corrected to normal vision. The healthy control group comprised 19 participants without neurological or psychiatric history matched to the patients on mean age and education (healthy controls; 10 females, mean age = 60.42 years, SD = 9.09; mean years of education = 11.00, SD = 2.82). Participant groups did not differ in age ($F_{2,39} = 1.80$; p = 0.17), education ($F_{2,39} = 0.33$; p = 0.71), or females/males ratio ($\chi^2 = 3.44$; p = 0.18). The sample size was based on our previous study of mind-wandering in vmPFC patients (Bertossi and Ciaramelli, 2016). Given the sample sizes, this study was adequately powered (80%) to detect large effects ($\eta_p^2 \approx 0.14$), but sensitivity was lower for medium ($\eta_p^2 \approx 0.06$) and small effects ($\eta_p^2 \approx 0.01$). Participants gave informed consent to participate in the experiment, which was performed in agreement with the Declaration of Helsinki and approved by the Bioethical Committee of the University of Bologna.

### 2.2. Lesion analysis

Patients' individual lesions, derived from the most recent MRI or CT scans were manually drawn by a trained neuroscientist directly on each slice of the normalized T1-weighted template MRI scan from the Montreal Neurological Institute distributed with MRIcro (Rorden and Brett, 2000). The MRIcro software was used to estimate lesion volumes (in cc) and generate lesion overlap images. Fig. 1 shows the extent and overlap of brain lesions in vmPFC patients. Brodmann's areas (BA) mainly affected were BA 10, BA 11, BA 24, BA 25, and BA 32, with the region of maximal lesion overlap in BA 11 (M = 14.41 cc, SD = 10.64 cc), BA 10 (M = 8.15 cc, SD = 8.17 cc), and BA 32 (M = 5.42 cc, SD = 5.82 cc). Gray matter loss in the vmPFC did not differ between the left and right hemispheres (left vmPFC: M = 17.10 cc, SD = 15.25 cc; right vmPFC: M = 14.27 cc, SD = 12.08 cc; $t_8 = 0.46$, p = 0.65). One patient also had damage to BA 45, BA 47, and BA 38 accounting for about 6%, 12%, and 8% of lesion size, respectively (excluding this patient from the analyses did not alter the results meaningfully; see Tables 1 and 2 of the Supplementary material).

### 2.3. Neuropsychological assessment

All participants received a standardized neuropsychological battery (**see** Supplementary material) mainly targeting memory and attentional/executive functions (see Table 1). General cognitive functioning was preserved across groups, as indicated by the scores obtained in the Raven Standard Matrices, which were within the normal range (i.e.,

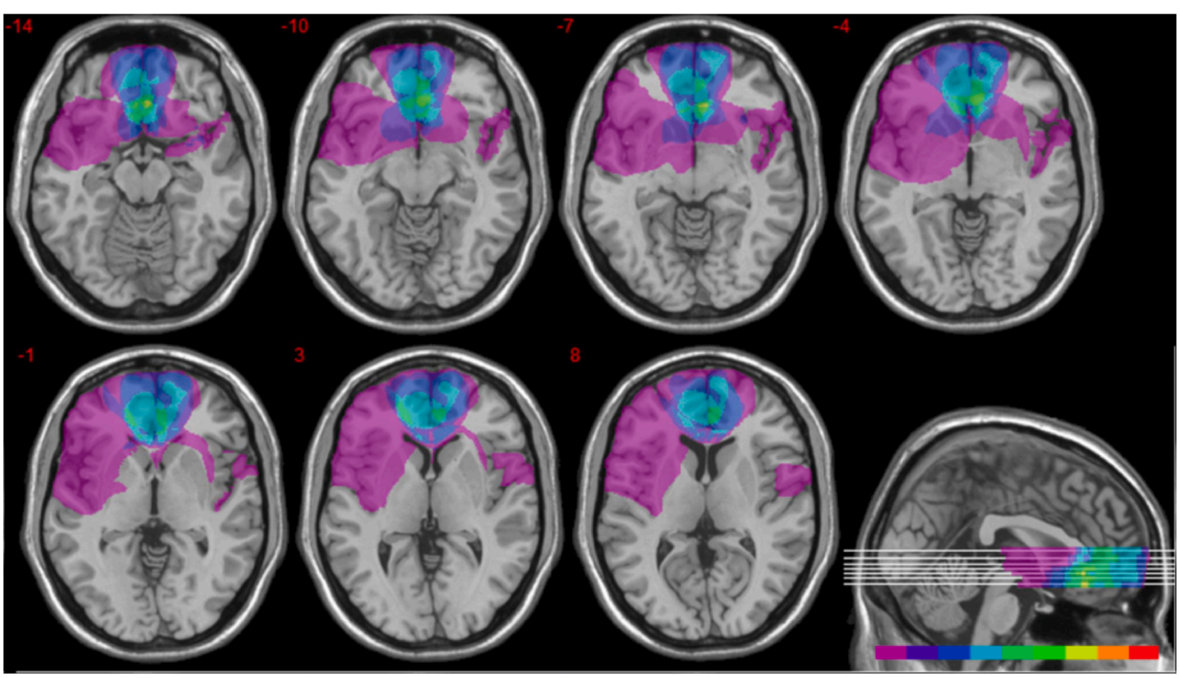


**Fig. 1.** Extent and overlap of vmPFC patients' brain lesions. Lesions are projected on the same seven axial slices of the standard Montreal Neurological Institute brain. The white horizontal lines on the sagittal view are the positions of the axial slices. Numbers above the axial views represent the z-coordinates of each slice. The color bar indicates the number of overlapping lesions, from 1 (purple) to 9 (red). Left hemisphere on the left side.

corresponding to an equivalent score ≥1; Spinnler and Tognoni, 1987), and similar across groups (Spinnler and Tognoni, 1987; $H_2 = 4.85$; $p = 0.09$; $\eta^2_R = 0.07$). Participant groups also reported normal (and similar) scores in verbal short-term memory, as assessed by the digit span test (Spinnler and Tognoni, 1987; $H_2 = 1.17$; $p = 0.55$; $\eta^2_R = 0.00$), working memory, as assessed with the digit span backward (Monaco et al., 2013; $H_2 = 2.02$; $p = 0.35$; $\eta^2_R = 0.00$), and long-term memory, as assessed in a prose-passage recall task (Spinnler and Tognoni, 1987; $H_2 = 2.20$; $p = 0.33$; $\eta^2_R = 0.02$). Turning to attention, participant groups exhibited normal (and comparable) performance in the Stroop test, in terms of both errors (Caffarra et al., 2002; $H_2 = 3.20$; $p = 0.20$; $\eta^2_R = 0.03$) and interference times ($H_2 = 4.47$; $p = 0.10$; $\eta^2_R = 0.06$). Performance at the Trail-Making Test, indicative of attentional/task switching abilities, was within the normal range but differed across groups (Giovagnoli et al., 1996; $H_2 = 16.98$; $p = 0.001$; $\eta^2_R = 0.39$): post hoc Dunn tests (Holm--corrected) showed that both vmPFC patients ($Z = 2.43$; $p = 0.03$) and control patients ($Z = 4.00$; $p = 0.001$) had higher difference scores than healthy controls, indicative of poorer performance, with no difference between the patient groups ($p = 0.31$).

### 2.4. *Vigilance task and assessment of off-task thought*

Participants were tested individually in a dimly lit room. They completed a modified version of a vigilance task developed by Schlagman and Kvavilashvili (2008; see also Vannucci et al., 2017). The task involved two conditions: the Standard condition and the Cued condition. In each trial of the Standard condition, a pattern of randomly distributed white horizontal or vertical segments (4.1 × 0.2 deg) appeared on the screen, against a black background (see Fig. 1). Participants were asked to press the spacebar whenever a pattern of vertical segments (target) appeared. The task consisted of 640 trials (39 targets), each lasting 2 s. A white fixation point (0.2 deg diameter) was presented in the centre of the screen for each trial. In the Cued condition, also comprised of 640 trials (39 targets), a verbal cue (e.g., "seaside"; 0.88 deg height) was presented right under the fixation point, in 120 of the 640 trials, at a rate of one every 3-6 trials. The verbal cues were selected from the Italian adaptation of a standardized pool of 800 word-phrases developed by Schlagman and Kvavilashvili (2008) (see Fig. 2; Vannucci et al., 2014). The task lasted ≈30 min in both conditions.

In both the Standard and Cued conditions, off-task thought was assessed through 16 'thought probes', appearing approximately one every 40 trials. Thought probes were presented visually, as a series of three screens. A first screen required participants to rate the degree to which immediately before the probe their attention was on-task (focused on performing the task) vs. off-task (focused on something else), on a Likert scale from 1 – 'completely on-task' to 7 – 'completely off-task'. If they answered that their attention was off-task (ratings 2-7), they were additionally required to classify their off-task experience as: (1) internal thoughts (mind-wandering; i.e., task-unrelated thoughts originated internally; e.g., "I can't wait to be at the concert"), (2) task-related thoughts (i.e., thoughts triggered by the task, but not necessarily useful to do the task; e.g., "this task is very boring"), (3) external distractions (i.e., thoughts triggered by stimuli in the environment or physical sensations; e.g., "Was that a thunder?", "I am thirsty"), and (4) unaware (if the thoughts were unclear or not easily classifiable into one category). In the Cued condition, participants could additionally classify their thoughts into the category (5) cued thought (i.e., thoughts triggered by a cue-word; e.g., "SEASIDE made me think of last summer in Greece"). If participants chose category 1 (in the Standard condition) or categories 1 and 5 (In the Cued condition), a third screen further probed them to specify if the thought they were having focused on the (1) past (e.g., "The holiday in Turin was the worst ever"), (2) present (e.g., "I wonder what my son is doing now"), (3) future (e.g., "I am seeing the dentist tomorrow"), or (4) atemporal, without a clear temporal connotation (e.g., "I never liked him anyway").

In both the Standard and Cued conditions, before the task participants were instructed on the different classes of off-task experiences assessed in the study. An instruction form was read aloud by the experimenter, who also verified comprehension to ensure a shared understanding across participants (see Supplementary material). Moreover, participants underwent a short pilot session comprising 20 trials (2 targets), 4 cue words, and 1 thought probe at the end. The software MATLAB R2015a (MathWorks) with Psychtoolbox was used to run the vigilance task and recorded accuracy, RTs, and ratings of off-task thoughts. Pupil size was also collected but not analysed in this report. The Standard and the Cued conditions were run approximately 1 week apart, in a counterbalanced order across groups ($\chi^2 = 0.069$; $p = 0.96$).

## 3. Results

### 3.1. *Vigilance*

Trials of the ongoing task with responses faster than 200 ms were excluded from the analyses (Standard condition: vmPFC = 1.5% trials, CP = 0.2% trials, HC, 0.4% trials; Cued condition: vmPFC = 2.7% trials, CP = 0.2% trials, HC, 0.1% trials). Group differences in the percentages of excluded trials were not significant in the Standard condition ($H_2 = 1.30$, $p = 0.52$) but they were in the Cued condition, with more trials excluded in vmPFC patients ($H_2 = 7.51$, $p = 0.02$). This was mainly due to two vmPFC patients who likely rested their hand on the spacebar inadvertently, generating a long series of button presses.

Table 2 portrays hit rates, false alarm rates, accuracy (hits – false alarms), and reaction times on correct responses (RTs) and the standard deviation (SD) of RTs for correct responses at the vigilance task by participant group and experimental condition. An ANOVA on endorsement rates with Trial (Target, Non-target), Condition (Standard, Cued),

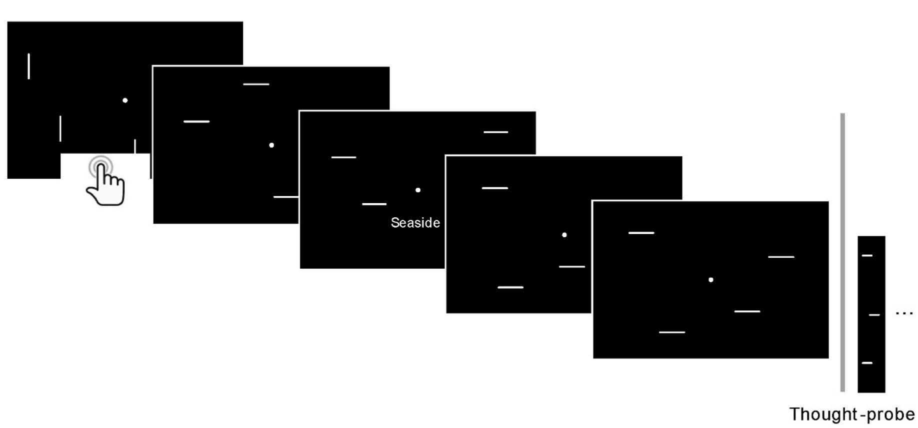


**Fig. 2.** Example experimental trial of the vigilance task (Cued condition).

**Table 2**
Hit rates, False-alarm (FA) rates, Accuracy (ACC; hit rates – false alarm rates), and response times (RT), and standard deviations (SD) of RTs in the vigilance task by group and experimental condition (mean and standard deviation).

| | Standard condition | | | | | Cued condition | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Hit Rates | FA rates | ACC | RT (ms) | SD RT (ms) | Hit Rates | FA rates | ACC | RT (ms) | SD RT (ms) |
| vmPFC patients | 0.97 (0.05) | 0.01 (0.01) | 0.96 (0.06) | 840 (126) | 160 (73) | 0.97 (0.04) | 0.01 (0.01) | 0.96 (0.05) | 873 (112) | 182 (75) |
| control patients | 0.97 (0.05) | 0.00 (0.00) | 0.97 (0.05) | 816 (215) | 150 (67) | 0.94 (0.12) | 0.00 (0.00) | 0.94 (0.12) | 803 (154) | 169 (71) |
| healthy controls | 0.97 (0.05) | 0.00 (0.00) | 0.97 (0.05) | 810 (122) | 152 (83) | 0.96 (0.08) | 0.00 (0.00) | 0.96 (0.09) | 814 (124) | 157 (68) |

and Group (vmPFC patients, control patients, healthy controls) as factors yielded a significant effect of Trial ($F_{1,39} = 35.12$, $p = 0.001$, $\eta_p^2 = 0.99$), such that participants made more hits than false alarms. No other effects or interactions were significant (all ps $> 0.36$, $\eta_p^2 < 0.03$). Accordingly, the ANOVA on accuracy with Group and Condition as factors yielded no significant effects ($F_{2,39} < 0.86$, $p > 0.36$, $\eta_p^2 < 0.03$ in all cases).

Turning to RTs, an ANOVA with Group and Condition as factors yielded no significant effects ($F_{2,39} < 0.80$, $p > 0.45$, $\eta_p^2 < 0.04$ in all cases), and so did the same ANOVA on the standard deviations of RTs ($F_{2,39} < 2.06$, $p > 0.15$, $\eta_p^2 < 0.05$ in all cases). These findings indicate that participant groups had a similar vigilance in the ongoing task, which was not significantly altered by the presence of word-cues.

### 3.2. *Off-task thought frequency*

One healthy control discontinued the Cued condition earlier and received only 13 out of 16 thought probes. Additionally, due to technical issues, in the Cued condition one vmPFC patient and one healthy control received 15 probes, and one vmPFC patient received 14 probes. In the Standard condition, three healthy controls received 15 probes. The number of probes received did not differ across groups either in the Standard condition (vmPFC patients: M = 16.00; control patients: M = 16.00; healthy controls: M = 15.84; $H_2 = 3.18$, $p = 0.14$) or in the Cued condition (vmPFC patients: M = 15.67; control patients: M = 16.00; healthy controls: M = 15.79; $H_2 = 3.03$, $p = 0.21$).

We calculated the frequency of each class of off-task experience (internal thoughts, thoughts triggered by word-cues, task-related thoughts, external distractions, unaware) as the number of off-task experiences participants reported for that category divided by the number of thought probes received, separately for the Standard (Fig. 3) and the Cued condition (Fig. 4). We assessed groups differences in the frequency of different classes of off-task experience separately, using Kruskal–Wallis one-way ANOVAs (the data were in most cases non-normally distributed) and Dunn post hoc tests (Holm-corrected) to determine which group difference drove the effect.

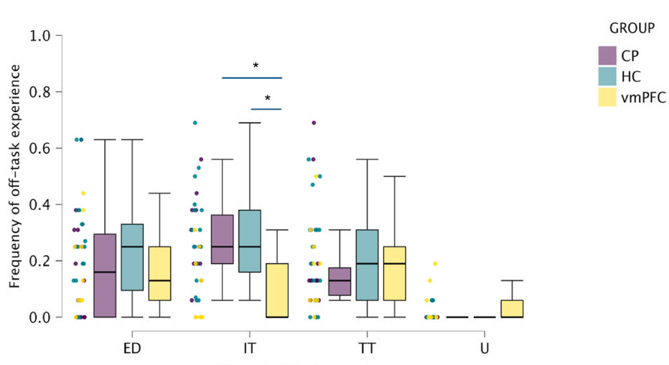


**Fig. 3.** Frequency of off-task experiences by participant group and type of off-task experience (IT = internal thoughts, TT = task-related thoughts, ED = external distractions, U = unaware) in the Standard Condition. Boxplots depict the median, first and third quartiles, and minimum and maximum (whiskers) of the data sets. *p < 0.05.

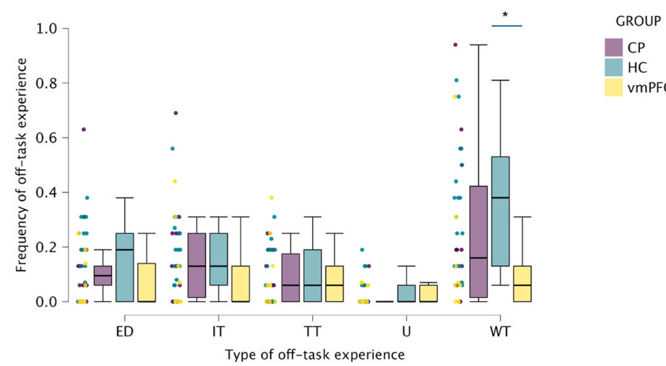


**Fig. 4.** Frequency of off-task experiences by participant group and type of off-task experience (IT = internal thoughts, WT = thoughts cued by a word, TT = task-related thoughts, ED = external distractions, U = unaware) in the Cued Condition. Boxplots depict the median, first and third quartiles, and minimum and maximum (whiskers) of the data sets. *p < 0.05.

As is apparent in Fig. 3, in the Standard condition vmPFC damage selectively reduced internal thoughts (mind-wandering), and no other types of off-task experience. The Kruskal-Wallis ANOVA on internal thoughts yielded a statistically significant group difference ($H_2 = 9.09$, $p = 0.01$; $\eta_R^2 = 0.18$). Post-hoc tests confirmed that vmPFC patients experienced fewer internal thoughts (mind-wandering) compared to healthy controls ($z = 2.84$; $p = 0.01$) and control patients ($z = 2.59$; $p = 0.02$), with no difference between the control groups ($p = 0.89$). By contrast, no groups difference emerged in external distractions ($H_2 = 1.06$; $p = 0.58$; $\eta_R^2 = 0.00$), task-related thoughts ($H_2 = 0.23$; $p = 0.89$; $\eta_R^2 = 0.00$), and thoughts of unclear origin ($H_2 = 5.08$; $p = 0.08$; $\eta_R^2 = 0.08$).

In the Cued condition, group differences in internal thoughts were no longer significant ($H_2 = 1.77$; $p = 0.41$; $\eta_R^2 = 0.00$), likely since most off-task experiences were now triggered by cue words (see Fig. 4**).** Indeed, mind-wandering triggered by cue words differed significantly across groups ($H_2 = 6.24$; $p = 0.04$; $\eta_R^2 = 0.11$), with lower scores in vmPFC patients compared to healthy controls ($z = 2.39$; $p = 0.04$), though not control patients ($z = 1.01$; $p = 0.31$), and no difference between the control groups ($p = 0.25$). As in the Standard condition, group differences in external distractions ($H_2 = 2.80$; $p = 0.24$; $\eta_R^2 = 0.02$), task-related thoughts ($H_2 = 0.14$; $p = 0.93$; $\eta_R^2 = 0.00$), and thoughts of unclear origin were not significant ($H2 = 4.06$; $p = 0.13$; $\eta_R^2 = 0.05$).

This first set of findings indicates that vmPFC damage leads to a drastic reduction in initiating mind-wandering endogenously (internal thoughts; Standard condition), and to a less severe impairment in initiating mind-wandering upon the provision of cue-words (Cued condition), but leaves unaffected other forms of externally driven forms of off-task experience, such as task-related thoughts and external distractions. The frequency of internal thoughts in the Standard condition ($r_{Spearman} = - 0.12$, $p = 0.59$) and of thoughts triggered by cue-words in the Cued condition ($r_{Spearman} = - 0.04$, $p = 0.86$) did not correlate with total lesion size in the patient groups.

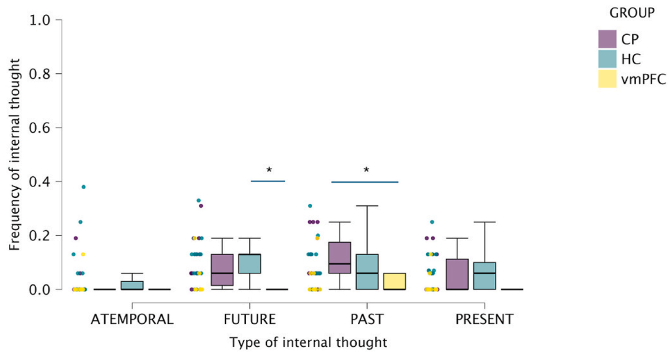


**Fig. 5.** Frequency of internal thoughts by participant group and temporal focus in the Standard condition. Boxplots depict the median, first and third quartiles, and minimum and maximum (whiskers) of the data sets. $*p < 0.05$.

### 3.3. *Temporal focus of mind-wandering*

We investigated whether vmPFC damage altered the temporality of mind-wandering, by comparing across groups the frequency of internal thoughts in the Standard condition (Fig. 5) and in the Cued condition (Fig. 6) belonging to each time category (past, present, future, atemporal) separately. We also investigated the temporality of thoughts triggered by cue words, as these are most often past-oriented (Fig. 7; Vannucci et al., 2017).

In the Standard condition, group differences in mind-wandering were present in internal thoughts oriented towards the future ($H_2 = 6.77$; $p = 0.03$; $\eta^2_R = 0.12$), such that vmPFC patients mind-wandered less towards the future than healthy controls ($z = 2.58$; $p = 0.03$), but not control patients ($z = 1.89$; $p = 0.11$), with no difference between the control groups ($p = 0.49$; Fig. 5). There were also group differences in past-oriented mind-wandering ($H_2 = 6.51$; $p = 0.04$; $\eta^2_R = 0.11$), with lower scores in vmPFC patients compared to control patients ($z = 2.55$; $p = 0.03$), but not healthy controls ($z = 1.56$; $p = 0.23$), and no difference between the control groups ($p = 0.23$). By contrast, there were no group differences in present-oriented or atemporal mind-wandering ($p > 0.23$ in both cases).

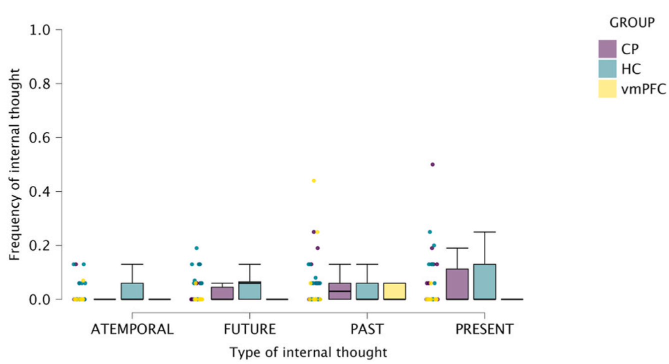


**Fig. 6.** Frequency of internal thoughts by participant group and temporal focus in the Cued condition. Boxplots depict the median, first and third quartiles, and minimum and maximum (whiskers) of the data sets.

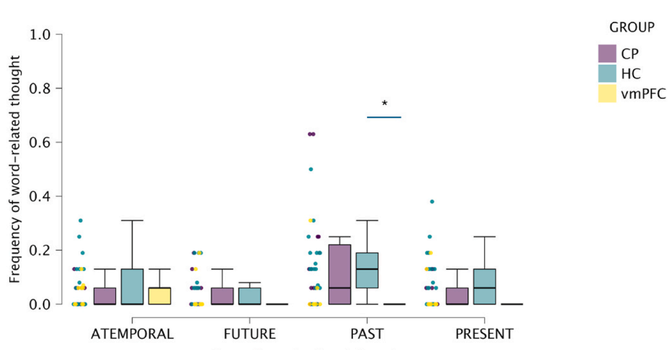


**Fig. 7.** Frequency of word-related thoughts by participant group and temporal focus in the Cued condition. Boxplots depict the median, first and third quartiles, and minimum and maximum (whiskers) of the data sets. $*p < 0.05$.

In the Cued condition, group differences in all temporalities of internal thoughts were non-significant ($p > 0.06$ in all cases; Fig. 6). As for mind-wandering cued by words, there was a significant group difference in past-oriented thoughts ($H_2 = 6.87$; $p = 0.03$; $\eta^2_R = 0.12$), with vmPFC patients reporting lower scores than healthy controls ($z = 2.62$; $p = 0.03$), but not control patients ($z = 1.62$; $p = 0.21$), and no difference between the control groups ($p = 0.29$; Fig. 7). No group difference emerged for future-oriented, present-oriented, or atemporal thoughts ($p > 0.11$ in all cases).

This second set of analyses shows that vmPFC damage reduced both future-oriented and past-oriented mind-wandering significantly.

## 4. Discussion

This paper investigated the specific role of vmPFC in mind-wandering, by contrasting the propensity towards endogenously generated mind-wandering with that of externally triggered forms of off-task experience (external distractions, task-related reflections) in vmPFC patients, control patients and healthy controls (Standard condition), and by studying the effect of the external provision of word cues capable to trigger mind-wandering (Cued condition).

We found that vmPFC patients have a significantly reduced tendency to mind-wander compared to brain-damaged and healthy controls. This deficit was apparent in a marked reduction of internal thoughts in vmPFC patients compared to the control groups (Standard condition). This finding confirms previous evidence of reduced mind-wandering following vmPFC damage (Bertossi and Ciaramelli, 2016; O'Callaghan et al., 2019; Philippi et al., 2021) or tDCS-induced inhibition (Bertossi et al., 2017b; Giacometti Giordani et al., 2023; Kam et al., 2022). This finding also aligns with fMRI evidence that regions of the MTL subsystem of the DMN, including vmPFC (Andrews-Hanna et al., 2010a, 2010b), are consistently engaged during mind-wandering (Christoff et al., 2009; Stawarkcyz et al., 2011; Fox et al., 2015; Konu et al., 2020; Smallwood et al., 2021), and may be specifically related to the generation of spontaneous thought (Christoff et al., 2016).

To begin to constrain the functional role of vmPFC in mind-wandering, this study, unlike previous studies (Bertossi and Ciaramelli, 2016; Bertossi et al., 2017b), also examined the effect of vmPFC damage on externally triggered forms of off-task experience. We found no effect of vmPFC damage on external distractions and task-related thoughts across experimental conditions. That is, while vmPFC damage precluded patients to experience task-unrelated and stimulus-independent thought (mind-wandering), it did not impair forms of off-task experience less removed from perceptual reality, because apparently triggered by an external stimulus or the ongoing activity. We recently observed a similar, selective reduction of mind-wandering but not external distraction after tDCS-induced inhibition of mPFC (Giacometti Giordani et al., 2023), which is consistent with fMRI evidence that although the DMN is engaged by stimulus-independent and by task-unrelated thought, it is maximally engaged by full-fledged mind-wandering with both aspects of separation from perceptual reality (Stawarkcyz et al., 2011).

The fact that vmPFC damage hindered mind-wandering selectively is hard to interpret as a problem in becoming aware of the content of one's thoughts in vmPFC patients (Smallwood and Schooler, 2015; Faber and Mills, 2018). Were this the case, patients should exhibit a general underreporting of all types of off-task experience, including task reflections and external distractions, while we observed a selective reduction of internal thoughts. As well, it does not seem that vmPFC damage rendered patients "stimulus-bound" or generally unable to decouple from direct experience: their attention could detach from the execution of the ongoing task and be captured by external stimuli and even (task-related) thoughts. This finding makes clinical sense, because even though vmPFC patients exhibit reduced mind-wandering (Bertossi and Ciaramelli, 2016), they appear even more distractable than healthy controls by task-irrelevant external information, for example during flanker or Stroop tasks (di Pellegrino et al., 2007; Ziaei et al., 2018). Even in the current task, vmPFC patients appeared as - if not more - distractable than controls. Although overall accuracy and RTs were comparable across groups, vmPFC patients produced a higher number of invalid responses in the Cued condition (i.e., trials removed during preprocessing), suggesting lapses in attention or response control.

Unexpectedly, vmPFC patients also proved weak at generating mind-wandering following the provision of verbal cues compared to healthy controls (Cued condition), which is not consistent with the hypothesis that the vmPFC plays a selective role in triggering mind-wandering endogenously. The frequency of word-cued mind-wandering, however, did not differ between vmPFC and control patients, and therefore deficits in cued mind-wandering do not appear to be as characteristic of vmPFC patients as deficits in spontaneous mind-wandering. Rather, they may depend on the increased cognitive demands generating cue-driven mind-wandering has compared to the attentional capture by external or task-related stimuli. Single words are minimal cues, and to be able to interact with memory traces they may need cue specification, semantic elaboration, and working memory processes that are weak in brain damaged patients (see Hurley et al., 2011).

Even though vmPFC patients did not evince normal levels of cued mind-wandering (Cued condition), vmPFC damage had the strongest impact on endogenously generated mind-wandering (Standard condition; see also Bertossi and Ciaramelli, 2016; O'Callaghan et al., 2019). Interestingly, the reverse might be true for patients with MTL lesions. Indeed, the frequency of endogenously generated mind-wandering is normal after hippocampal damage (McCormick et al., 2018b) or in Alzheimer's disease (O'Callaghan et al., 2019), while cued mind-wandering was found impaired in the prodromal stages of Alzheimer's disease (Niedzwienska and Kvavilashvili, 2018). This weak double dissociation is compatible with the idea that, within the MTL subsystem of the DMN, the vmPFC and the MTL play complementary roles in mind-wandering, with the vmPFC primarily involved in the initiation of spontaneous thought and the MTL in fueling mind-wandering with context-rich content based on pattern-completion mechanisms (McCormick et al., 2018; Ciaramelli and Treves, 2019; Kvavilashvili et al., 2020; Viol et al., 2021).

vmPFC is closely linked to schema-related processing (Moscovitch et al., 2016; Gilboa and Marlatte, 2017), including the self-schema (Stendardi et al., 2023) and event scripts (Stendardi et al., 2025), and therefore may drive the construction of self-related mnemonic content by the hippocampus (Verfaellie et al., 2019). Accordingly, magnetoencephalography studies show synchronized engagement of the vmPFC and hippocampus during autobiographical memory retrieval and scene construction, with vmPFC activity driving hippocampal activity (Barry et al., 2019; McCormick et al., 2020; Monk et al., 2021). On this view, vmPFC patients would not fail to mind-wander because they cannot go off-task, but because they do not construct the thoughts that normally make our mind wander. Consistent with this idea, in the present study vmPFC damage tended to reduce future-oriented and past-oriented mind-wandering (Standard condition). Similarly, in the Cued condition, when word-cued mind-wandering (typically past-oriented; Vannucci et al., 2017) was prominent, vmPFC patients tended to show reduced past-oriented thought. By contrast, we found no group differences in present-oriented or atemporal mind-wandering, which occurred at lower rates across groups. These findings are consistent with fMRI evidence showing increased functional correlations within the MTL subsystem of the DMN in individuals with high rates of future- and past-oriented thoughts at rest (Andrews-Hanna et al., 2010b), and vmPFC activation in association with mind-wandering with episodic or social features (Konu et al., 2020). Within a dynamic framework of mind-wandering (Christoff et al., 2016), vmPFC-mediated schemas may function as (automatic) constraints on thought, biasing it toward self-relevant memories, and shaping its temporal progression (Zamani et al., 2022; Kucyi et al., 2023). Computationally, schemas may give rise to "latching" dynamics (Treves, 2005), enabling sequential transitions between attractor-like representations, particularly under conditions of reduced hippocampal input (Ryom et al., 2024). Empirically testing these proposals would require measuring not only the content of thought (which our experiment targeted) but also its variability (Zamani et al., 2022).

We end by highlighting the limitations and future directions of this research. One limitation is sample size, which constrained the sensitivity of our analyses. This limitation may have prevented us from detecting subtler group differences, and from exploring additional interesting variables, such as the potential differential roles of the right versus left vmPFC in mind-wandering. In addition, our paradigm assessed only probe-caught mind-wandering and is therefore primarily sensitive to awareness of mental content. The findings indicate that vmPFC patients did not report mind-wandering, and that his was not secondary to a deficit in becoming aware of mental content. Indeed, vmPFC patients reported other types of mental content at normal rates (including task-related thoughts). However, because participants were externally probed about their mental experiences, the task cannot address potential impairments in meta-awareness of mind-wandering or other forms of off-task experience. To address this question, future studies should aim to combine and contrast self-caught and probe-caught measures of mind-wandering (e.g., Sayette et al., 2009; Smallwood and Schooler, 2015; Seli et al., 2017; Cantarella et al., 2025). Finally, as anticipated, vmPFC patients in the current task exhibited reduced mind-wandering but also subtle performance failures, suggesting that reduced mind-wandering did not render them less distractible overall, but presumably less susceptible to internal distraction (see also di Pellegrino et al., 2007; Giacometti Giordani et al., 2023). Future studies designed to investigate the relationship between thought-probe data and behavioral markers of attentional fluctuations (e.g., Seli et al., 2013) could confirm whether different types of distracting information (external vs. internal) are differentially associated with performance failures in healthy controls versus vmPFC patients.

For the time being, we have shown that vmPFC damage impairs endogenously generated mind-wandering and, to a lesser degree, even the tendency to engage in mind-wandering when potential cues are provided, while leaving unaffected other forms of off-task thought that are triggered by environmental stimuli or the task at hand. These findings suggest that vmPFC is necessary for the spontaneous construction of (past and future) events capable to attract attention inward, away from the here and now. Reduced mind-wandering in patients with vmPFC damage may limit their ability to mentally explore information that is not immediately present, potentially impairing everyday planning, prospective and counterfactual thinking, and the capacity for fantasizing and self-reflection.

## CRediT authorship contribution statement

**Elisa Ciaramelli:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Virginia Pollarini:** Software, Methodology, Investigation, Data curation. **Andrea Crisafulli:** Software, Methodology, Data curation, Conceptualization. **Alessia Ferretti:** Software, Methodology, Data curation. **Manila Vannucci:** Writing – review & editing, Methodology, Data curation, Conceptualization.

## Ethics statement

The study was reviewed and approved by the Bioethic Committee of the University of Bologna. Participants provided their informed consent to participate in this study.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuropsychologia.2026.109438.

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