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ORIGINAL ARTICLE

# In Medio Stat Virtus: intermediate levels of mind wandering improve episodic memory encoding in a virtual environment

Philippe Blondé[1] · Dominique Makowski[1] · Marco Sperduti[1] · Pascale Piolino[1,2]

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## Abstract

Episodic memory encoding is highly influenced by the availability of attentional resources. Mind wandering corresponds to a shift of attention toward task-unrelated thoughts. Few studies, however, have tested this link between memory encoding and mind wandering. The goal of the present work was to systematically investigate the influence of mind wandering during encoding on episodic memory performances in an ecological setting. Fifty-two participants were asked to navigate in a virtual urban environment. During the walk, they encountered different scenes that, unbeknownst to the participants, were target items presented in a subsequent recognition task associated with a Remember–Know–Guess paradigm. Each item triggered, after a random interval, a thought probe assessing current mind wandering. We found a significant linear positive relationship between the ratio of correctly recognized items and the overall mind wandering reported after the task. Moreover, we found a quadratic reversed U-shaped relationship between the probability of giving a 'Remember' response and both on-line and mind wandering reported a posteriori. The nearer to the medium value the level of mind wandering was, the higher was the probability to have a recollection-based recognition. Our results indicate that in a complex environment, the highest probability of actually remembering a scene would be when participants present a medium attentional level: neither distracted by inner thoughts nor too focused on the environment. This open attentional state would allow a better global processing of the environment by preventing one's attention from being captured by internal thoughts or narrowed by an over-focusing on the environment.

## Introduction

Who has never experienced the situation of being in a boring talk, spending most of the time thinking about something else and, afterward, being clueless when trying to recall what the speaker was talking about? It seems obvious that memorization will be hindered when not paying attention. However, while there is an abundant literature investigating how attentional manipulations (e.g., divided attention paradigms) impact memory, few studies have tested the link between spontaneous attentional fluctuation (mind wandering) and memory encoding. More specifically, to our knowledge, none has tested this link in ecological conditions. Thus, this study aims at expanding the field of research of attention and memory by testing the impact of mind wandering on episodic memory encoding, using a virtual reality paradigm.

Episodic memory is the long-term memory system responsible for encoding and storing information about specific events retrieved alongside their spatio-temporal context (Tulving, 1972, 2002). According to the dual

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✉ Philippe Blondé
philippe.blonde93@gmail.com

Dominique Makowski
dom.makowski@gmail.com

Marco Sperduti
marco.sperduti@parisdescartes.fr

Pascale Piolino
pascale.piolino@parisdescartes.fr

[1] Laboratoire Mémoire, Cerveau et Cognition (URP 7536), Institut de Psychologie, Université de Paris, 71 avenue Ed. Vaillant, 92100 Boulogne Billancourt, Ile de France, France

[2] Institut Universitaire de France, Paris, France

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processes model (Wixted, 2007; Yonelinas, 1994), there are two ways to recognize previously encoded information: from recollection or from familiarity (Yonelinas, 2001). On one hand, a recollection-based recognition corresponds to a conscious remembering of both the item and the spatial and temporal context associated with it. This state of consciousness is associated with a mental time travel allowing to revive the event (Hasselmo, 2009; Tulving, 2002). On the other hand, familiarity-based recognition is based on semantic processes, and is characterized by the absence of contextual association. The two processes are independent and can be influenced separately (Gardiner & Java, 1996). One major factor determining the ability to retrieve an item is the quality of its encoding (Atkinson & Shiffrin, 1971; Craik & Lockhart, 1972), and among the different processes influencing memory encoding, attention plays a crucial role (Chun & Johnson, 2011; Chun & Turk-Browne, 2007). Many studies have pointed out the influence of attention on memory encoding, mainly through divided attention paradigms (Fernandes & Moscovitch, 2000). Indeed, dividing attention between a memory and a concurrent task limits the amount of cognitive resources available for each of them, and results in a decrease in memory performances (Craik, Naveh-Benjamin, Govoni, & Anderson, 1996; Jennings & Jacoby, 1993). The effect of divided attention is especially important during the encoding phase, while its effect during retrieval is either dependent on the nature of the competing task (Fernandes & Moscovitch, 2000; Wammes & Fernandes, 2016) or negligible (Iidaka, Anderson, Kapur, Cabeza, & Craik, 2000; Naveh-Benjamin, Craik, Guez, & Dori, 1998). The opposite is also true: facilitating attentional treatment during encoding improves perceptual processing and increases the probability of a successful recognition (Sperduti, Armougum, Makowski, Blondé, & Piolino, 2017; Turk-Browne, Golomb, & Chun, 2013; Uncapher, Hutchinson, & Wagner, 2011). Concerning the influence of attention on the consciousness state associated with recognition, it appears that dividing attention at encoding leads to a specific diminution of the rate of Remember responses (Curran, 2004; Yonelinas, 2001), while leaving Know responses relatively unaltered (Gardiner & Parkin, 1990).

Altogether, these results highlight the critical role of attentional processes for a successful encoding. However, most of the studies have tested the influence of attention on memory in a laboratory setting and with simple stimuli such as static images (Wammes & Fernandes, 2016) and words (Craik et al., 1996; Iidaka et al., 2000; Mulligan, 1998). These conditions are certainly quite far from the attentional and memory demands encountered in everyday life situations. An increasing number of works has pointed out the pertinence of employing virtual reality for studying both attentional (Bier, Ouellet, & Belleville, 2018; Camara Lopez, Deliens, & Cleeremans, 2016; Harand, Mondou, Chevanne, Bocca, & Defer, 2018; Lengenfelder, Schultheis, Al-Shihabi, Mourant, & DeLuca, 2002; Plancher, Gyselinck, & Piolino, 2018), and memory processes (Abichou et al., 2019; Abichou, La Corte, & Piolino, 2017; Jebara, Orriols, Zaoui, Berthoz, & Piolino, 2014; La Corte, Sperduti, Abichou, & Piolino, 2019; Ouellet, Boller, Corriveau-Lecavalier, Cloutier, & Belleville, 2018; Plancher, Barra, Orriols, & Piolino, 2013; Plancher, Gyselinck, Nicolas, & Piolino, 2010; Plancher, Tirard, Gyselinck, Nicolas, & Piolino, 2012; Sauzéon, N'Kaoua, Arvind Pala, Taillade, & Guitton, 2016) in a more ecological way. Moreover, another way to study more ecologically the influence of attention on memory would be by assessing one common attentional phenomenon that everybody experiences on a daily basis: mind wandering.

Defining mind wandering is a complex matter, as it encompasses many different and sometimes contradictory situations. Classically, mind wandering is defined as a state of consciousness characterized by the experience of thoughts unrelated to the ongoing task (Giambra, 1989), attentional lapses (Smallwood, Davies, et al., 2004), or stimulus-independent thoughts (Antrobus, 1968). All these terms define overlapping phenomena, but some aspects of mind wandering are still, to this day, a matter of debate (see Seli et al, 2018a, b for a review). In the present paper, we focus more specifically on the variations of mind wandering during a task. Indeed, mind wandering is a dynamical process characterized by the spontaneous fluctuation of the attentional focus between different cognitive states, in particular from an ongoing task to inner thoughts (Christoff, Irving, Fox, Spreng, & Andrews-Hanna, 2016). As mind wandering tends to occur in about 45% of our daily mental activities (Killingsworth & Gilbert, 2010), it implies that attention can vary in a gradual way between the task at hand and irrelevant thoughts, as it would be impossible to proceed through daily activities if mind wandering was an all or nothing process. Thus, to take into account this dynamic, it is important to have a continuous measure of mind wandering that allows the participant to determine the importance of its attentional variations.

The studies testing the specific influence of mind wandering on memory focus mainly on text comprehension and images/words recall. As expected, mind wandering during both incidental and intentional encoding leads to a lesser recall of information (deBettencourt, Norman, & Turk-Browne, 2018; Seibert & Ellis, 1991; Smallwood, O'Connor, Sudberry, Haskell, & Ballantyne, 2004; Smallwood, O'Connor, Sudbery, & Obonsawin, 2007), a higher rate of false recognition (Smallwood, Baracaia, Lowe, & Obonsawin, 2003) and a worsened understanding of the material (Farley, Risko, & Kingstone, 2013; Feng, D'Mello, & Graesser, 2013; Risko, Anderson, Sarwal, Engelhardt, & Kingstone, 2012; Schooler, Reichle, & Halpern, 2005).

Concerning the state of consciousness associated with recognition, one study based on electrophysiological findings pointed out that mind wandering hinders recollection-based but not familiarity-based word recognition (Riby, Smallwood, & Gunn, 2008). In their study, no explicit measure of recollection/familiarity was used and assessment of mind wandering was conducted retrospectively, using a questionnaire to distinguish subjects with high and low frequency of task-unrelated thoughts.

Our study's purpose was to extend the findings of Riby et al. (2008) by adding an online and systematic evaluation of mind wandering coupled with explicit measures of recollection/familiarity for each item in order to compute a predictive model of recognition. Moreover, to provide an ecological assessment of the interplay between attention and memory, we used virtual reality to simulate the incidental encoding of naturalistic scenes during the navigation in a virtual town. Mind wandering was assessed with online thought probes occurring at the encoding of each scene. Then, we tested items recognition and the associated state of consciousness using the Remember-Know-Guess paradigm (Gardiner, 1988; Gardiner, Ramponi, & Richardson-Klavehn, 1998; Tulving, 1985). We hypothesize that the level of attention (i.e., level of mind wandering) allocated to the environment would negatively predict the probability of successfully recognize scenes of the environment and having a recollection-based recognition.

## Material and methods

### Participants

Fifty-nine participants (52 women/7 men, mean age = 21.04 ± 2.4 years) voluntarily attended to the present experiment after signing an informed consent. They were all students in the University of Paris and were granted a credit necessary to complete their course for participating in this experiment. We used the z-score method to detect and remove outliers in our data. In order to exclude any participant presenting attentional or mood deficits, we removed all participants scoring above the 99th percentile (2.3 standard deviations) in the following measures: PHQ-4 depression scale, PHQ-4 anxiety scale, accuracy score at the SART and hit rate at the SART (see "Material and methods" section for more information on the questionnaires and tasks employed as exclusion criteria). This led to the exclusion of three participants. We also removed three participants presenting a score above three out of ten in two suicide tendency questions. Lastly, we removed one participant reporting a mind wandering level of 0 ('totally focused on the environment') at each of the thought probes, as this score is both highly improbable and doesn't allow the calculation of a *Z* score used in further analyses. The final sample was composed of 52 participants (46 women/6 men, mean age = 21.08 ± 2.54 years).

### Questionnaires

As mood can have an impact on attentional performances during the task (Killingsworth & Gilbert, 2010; Poerio, Totterdell, & Miles, 2013; Smallwood, Fitzgerald, Miles, & Phillips, 2009; Smallwood & O'Connor, 2011), we tested our participant's current emotional state with the Positive and Negative Affect Schedule (PANAS; Watson, Clark, & Tellegen, 1988), a 20-items scale evaluating positive and negative mood. We also used the Mind Wandering Questionnaire (MWQ; Mrazek, Phillips, Franklin, Broadway, & Schooler, 2013), a short 5-items questionnaire to evaluate our participants' natural tendency to experience episodes of mind wandering. Lastly, we included the Patient Health Questionnaire (PHQ-4; Kroenke, Spitzer, Janet, Williams, & Lö, 2009; Löwe et al., 2010), to which we have added two questions asking the rate of suicidal thoughts in the past 10 days, resulting in a quick evaluation of depressive and anxiety disorders. This questionnaire was included in order to remove participants presenting high results, as they may present a different pattern of mind wandering than healthy subjects (Deng, Li, & Tang, 2014; Hoffmann, Banzhaf, Kanske, Bermpohl, & Singer, 2016; Marchetti, Koster, & De Raedt, 2012; Stawarczyk, Majerus, & D'Argembeau, 2013).

### Attentional task

In order to have an experimental measure of our participants' attentional abilities, they had to perform a Sustained Attention to Response Task (SART; Robertson, Manly, Andrade, Baddeley, & Yiend, 1997). In this test, numbers from 0 to 9 were presented in quick succession in the center of the screen. Each time the participants saw a number, they had to press the space bar as quickly as possible unless the stimulus was a 3. If a 3 was displayed, they had to inhibit their response and waited for the stimulus to disappear. Each number was presented 25 times (250 items in total) in a random order separated by a fixed interval of 900 ms and stayed on screen until the subject's response (up to 500 ms). See data analysis section for a description of SART scores.

### Memory task

#### Incidental encoding

The virtual environment consisted of an in-house virtual town made with Unity 3D. The participants navigated through the environment with an Xbox controller. The instruction was to go to the train station, following guiding signs dispatched along the road. It was specified that it was not a speed task, and the instruction emphasized the fact that the participants needed to pay attention to their environment in order to detect the signs and orientate themselves. They were not told that, afterward, they would have to perform a memory task (incidental encoding). The environment consisted of a typical modern city with graphical assets based on the Parisian architecture and an urban audio background. In order to complete the task, participants had to follow one route where they encountered various landmarks such as a market, a church or a park (other routes were dead ends). Dispatched regularly alongside the road, 8 critical scenes were included in the environment to be tested later in the recognition task (e.g., a woman petting a cat, a man taking a picture of a statue, etc.). They were characterized by a unique animation or asset but were not highly salient scenes, to avoid an automatic capture of attention. In order to have an estimation of mind wandering during the incidental encoding of each item, the apparition of a though probe was triggered after participants walked past the scenes, at a random interval of 1–3 s (see Fig. 1a). As such, the critical scenes weren't in the participant's field of vision when they answered the probe. These thought probes asked participants 'Where is your attention focused on, right now?'. To answer these questions, they had to respond on a visual analogical scale ranging from 'My attention is entirely focused on the environment' to 'My attention is entirely focused on my thoughts' corresponding to scores ranging from 0 to 10. In total, 8 probes were administered, providing a measure of the evolution of mind wandering during the task (interval inter-probes: 40.69 s ± 8.63). Navigation lasted for about 5 min (5.59 m ± 0.62). In order to complement our online measures and to circumvent more precisely the content of our participant's thoughts, they were asked, right after the navigation, to estimate the overall degree of mind wandering they experienced. They were presented a diagram based on the though probes elaborated by Stawarczyk, Majerus, Maj, Van der Linden and D'Argembeau (2011), presenting four attentional categories corresponding to the crossing of two orthogonal classification axes: focused on the environment/not focused on the environment, and stimulus-dependent/stimulus independent (see Fig. 1b). For each category, participants had to indicate the amount of time (in percentage) they spent in that specific state of mind during the navigation. In line with the more prototypical operationalization of mind wandering (Seli, Kane, Smallwood, et al., 2018a, b), the category 'stimulus independent thoughts/not focused on the environment' serves here as the main indicator of the overall quantity of mind wandering experienced during the task.

### Recognition task

Memory was tested using a recognition task (yes–no) followed by a Remember–Know–Guess paradigm (RKG; Gardiner, 1988; Gardiner, Ramponi, & Richardson-klavehn, 1998). The eight critical scenes were presented without contextual clues alongside with 8 linked distractors (similar to the critical scenes but with slightly different characters and objects in the scenery) and 8 non-linked distractors (scenes not present in

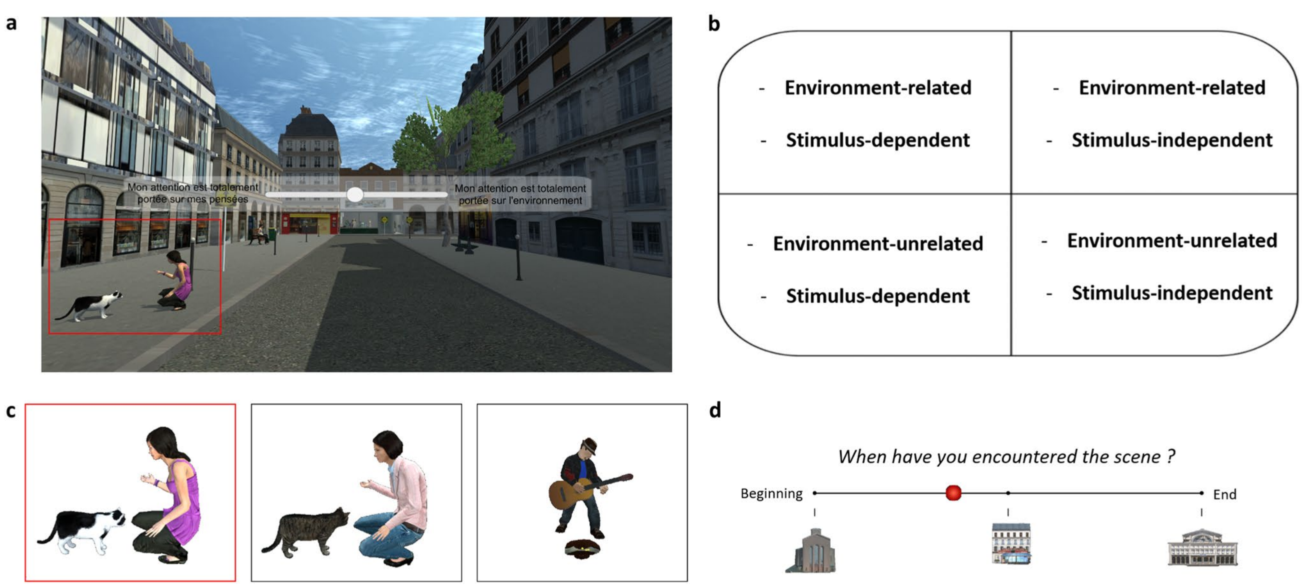


**Fig. 1** **a** A thought probe appearing on screen after passing by a critical item (to the left); **b** Final thought probe based on Stawarczyk et al. (2011) completed after the virtual reality task; **c** From left to right: a target item, a linked distractor and a non-linked distractor; **d** Scale used to locate the temporal position of a scene

the virtual city and without any pictorial link with the target scenes (see Fig. 1c) in a randomized order. The participants had to indicate if the scene was present in the environment or not. If the subjects indicated that a scene was present in the environment, they had to specify the nature of their answer according to the standard RKG procedure (Gardiner, 2001): if they remembered the scene (i.e., if they experienced a subjective mental time travel allowing them to revive the scene in its context), if they knew that the scene was presented (they were sure of seeing the scene but their memory didn't include a revivification of the context), or if it was just a guess (an intuition that the scene was in the environment). The meaning of each answer was explained to the participants. After that, participants were tested on their contextual memory (both spatial and temporal). First, they had to indicate on which side of the road the scene occurred (to the left or to the right). Then, they were presented a temporal scale representing their navigation in the virtual environment. Three landmarks clearly visible by the participant during his navigation (the church to mark the beginning, the bar at midway and the train station at the end) were always depicted on the scale. The layout of the virtual town forced the participant to face each of these landmarks to assure their visibility. The participants had to place on the scale when they encountered the scene (see Fig. 1d). See data analysis section for a description of memory scores.

### Procedure

Participants were evaluated individually in a quiet room of the Institute of Psychology. They sat in a chair at approximately 70 cm of a 22.9″ computer screen. Then, they were given an Xbox controller and headphones, and were asked to navigate in a training virtual environment in order to habituate them to the controls before performing the Virtual Reality task. After completion of the navigation, they started the second part of the experiment, which was entirely informatized and programmed in Python 3.6, using the Neuropsydia module (Makowski & Dutriaux, 2017). First, participants answered to various demographic questions (Age, Sex, Education level, Frequency of video game usage…) and completed the PANAS. Then, they carried out the SART. These tests acted as an interference task (for about 10 m) before the recognition task. And finally, participants completed the MWQ and the PHQ_4. The whole experiment lasted for about one hour.

## Results

### Data analysis

We calculated the accuracy score of the SART responses based on the percentage of correctly rejected stimuli (total of '3' presented without a response) and the hit score based on the percentage of correctly responded stimuli (total of numbers other than '3' with a response). To estimate the ability to discriminate between targets and distractors in the recognition task, we computed a non-parametric discrimination index ($A'$) based on the signal detection theory separately for the linked and the non-linked distractors. For the RKG task, we have first calculated the ratio of correctly recognized items. Then, selecting only the correctly recognized items and excluding the G responses, we have computed a ratio of R responses to the number of correct recognitions. For the context memory task, we have calculated a ratio of correctly identified spatial positions, and lastly, we have calculated the temporal estimation of our participants as the absolute difference between the objective time when the scene was encountered, and the subjective response of the subject indicated on the temporal scale.

All statistical analyses were conducted with the software R 3.5.1 (R Development Core Team 2005). We chose to perform Bayesian analysis on our data, as this approach is deemed to be more reliable, accurate, more straightforward to interpret and generally recommended by the recent guidelines of statistics in psychology (Andrews & Baguley, 2013; Etz & Vandekerckhove, 2016; Kruschke, 2010; Kruschke, Aguinis, & Joo, 2012; Wagenmakers et al., 2018). Bayesian analysis were conducted using the packages *rstanarm* (Carpenter et al., 2017; Gabry & Goodrich, 2016) and were interpreted with the *psycho* package (Makowski, 2018). For each model, we will report the probability of direction (pd; an index assessing the existence of an effect), the median and credible interval of the posterior distribution (the distribution of possible values for an effect, given our data), and the $R^2$ of the model (corresponding to the percentage of explained variance of the model, as in the frequentist framework).We will consider an effect as 'significant' if the associated pd is above 95% (Makowski, Ben-Shachar & Lüdecke, 2018). For each measures of memory, when computing a predictive model, we tested both the linear and quadratic trends. For the sake of clarity, we reported in the following only the significant trends within the models. Detailed results and descriptive data are reported in supplementary material.

### Convergent validity of mind wandering measures

First, in order to assess the convergent validity of our measures of mind wandering, we fitted a linear Bayesian model to test if the score of a posteriori mind wandering (the final probe) was predicted by the mean mind wandering score reported during the navigation. The model had an explanatory power ($R^2$) of about 5.73%. The effect had a 95.33% probability of being positive (median = 1.84, 90% CI [0.09, 3.61]). Thus, it is possible that a linear relationship existed between our two main mind wandering measures. The higher the percentage of mean mind wandering score during the task was, the higher the mind wandering reported a posteriori was too.

We also tested if these measures were representative of the natural mind wandering tendency, measured with the MWQ. We fitted two Bayesian linear models, one predicting the a posteriori mind wandering, and the other predicting the mean mind wandering score of the thought probes with the mean MWQ score. The first model had an explanatory power ($R^2$) of about 12.61%. The effect of MWQ on a posteriori mind wandering had a probability of 99.38% of being positive (median = 7.05, 90% CI [2.95, 11.80]). Thus, it is probable that a linear relationship between these two measures existed. The second model had an explanatory power ($R^2$) of about 1.02%. The effect of MWQ on the thought probes' scores had a probability of 63.8% of being positive (median = 0.13, 90% CI [− 0.46, 0.72]), so it is uncertain if a relationship between MWQ score and mind wandering score tested during the task existed. To further test the extent to which a posteriori mind wandering was predicted by our participant's mood, we fitted two linear models, one with the negative score of the PANAS and the other with the positive score. It appears the first model had an explanatory power ($R^2$) of about 5.79%. The effect of negative PANAS score had a probability of 96.05% of being positive (median = 10.11, 90% CI [0.06, 19.30]). This means that it is possible that a linear relationship exists between the negative mood score measured by the PANAS and the mind wandering reported a posteriori. The second model had an explanatory power ($R^2$) of 1.27%. The effect of positive PANAS score had a probability of 73.28% of being negative (median = − 2.11, 90% CI (− 7.80, 3.25)], thus it is uncertain if a relationship exists with the mind wandering reported a posteriori. Concerning the *online* mind wandering score, none of the predictors were found to be significant (see Fig. 2 for an overview).

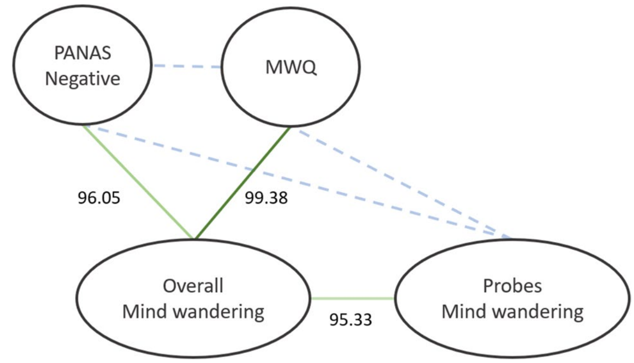


**Fig. 2** Convergent validity between our main measures based on the probability of detection of each model (in %). Dotted lines correspond to pd < 90%

**Table 1** Descriptive statistics of the RKG answers and contextual memory tests (for correctly recognized items only)

| | Mean | Spatial recognition ratio | Mean temporal deviation (s) |
|---|---|---|---|
| Remember | 1.49 (1.54) | 0.59 (0.29) | 71.41 (37.13) |
| Know | 0.75 (0.8) | 0.42 (0.35) | 91.58 (58.97) |
| Guess | 0.88 (0.97) | 0.31 (0.27) | 108.60 (63.01) |

## Verification of memory scores

Concerning our memory measures (see Table 1), we first conducted a Bayesian t test between the $A'$ for linked and non-linked distractors, to assess if our participants were sensitive to this manipulation. The test suggested a strong evidence (BF = 14.03) in favor of a difference between the $A'$ for non-linked distractors (mean $A' = 3.8 \pm 6.21$) and linked distractors (mean $A' = 1.8 \pm 3.79$). Then we tested if the subjective state of consciousness associated with recognition (either Remember, Know or Guess), was associated with the objective measures of contextual memory (spatial and temporal). First, we fitted a Bayesian linear model to predict the ratio of correctly recognized spatial location with the state of consciousness associated with recognition. The model had an explanatory power ($R^2$) of about 13.5%. Within this model, the spatial recognition ratio associated with R responses (0.56 ± 0.29) is likely to be greater than the ratio associated with K responses (0.42 ± 0.35) as the difference between them had a probability of 97.95% of being negative (median = − 0.16, 90% CI [− 0.30, − 0.04]). Also, it is almost certain to be greater than the one associated with G responses (0.3 ± 0.27) as the difference between R and G responses had 99.95% of being negative (median = − 0.27, 90% CI [− 0.40, − 0.14]). However, the ratio associated with K responses is uncertain to be greater than G responses one, as the difference between K and G responses had 92.10% of being negative (median = 0.11, 90% CI [− 0.03, 0.24]). Then, we fitted another Bayesian linear model to predict the temporal estimation of the item with the state of consciousness associated with its recognition. The model had an explanatory power ($R^2$) of about 8.2%. It is uncertain if the temporal estimation associated with R responses (71.41 s ± 37.13) is more precise than the estimation associated with K responses (91.58 s ± 58.97) as the difference between R and K responses had 92.05% of being positive (median = 18.96, 90% CI [− 3.96, 40.48]). However, temporal estimations associated with R are almost certain to be more precise than the estimation associated with G responses (108.60 s ± 63.01) as the difference between R and G responses had 99.55% of being positive (median = 35.16, 90% CI [12.53, 55.82]). The difference between estimations associated with K and G responses is uncertain as it had 87.55% of being positive (median = 15.85, 90% CI [− 5.85, 38.19]). (see Table 1 for a summary of contextual memory scores associated with R, F or G responses).

### Mind wandering and memory

For the subsequent analysis, we computed subject-wise *Z* scores of the mind wandering scores reported at each thought probes.

We assessed the relationship between the a posteriori reported mind wandering and the ratio of correctly recognized items by fitting a Bayesian linear model. The model had an explanatory power ($R^2$) of about 7.48%. Within our model, the linear trend had a 95.28% chance of being negative (median = − 0.32, 90% CI [− 0.6, 0.02]). This indicates the possible existence of a negative linear relationship between mind wandering and item memory. We also fitted a mixed Bayesian logistic model (with subjects and items as random effects) to test if the mind wandering score reported at each probe predicted the probability of correctly recognizing the associated item. The model had an explanatory power ($R^2$) of about 6.33%. The linear relationship had an 89.25% of being negative (median = − 2.89, 90% CI [− 6.55, 1.09]), thus it is uncertain if a relationship exists between these two measures.

After testing the influence of mind wandering on the ability to recognize an item, we assessed its possible influence over the state of consciousness associated with the retrieval of the item. We first fitted a Bayesian linear model to predict the ratio of Remember answers, with the a posteriori mind wandering score as predictor. The model had an explanatory power ($R^2$) of about 12.68%. Within this model, the effect of the quadratic trend had a probability of 97.43% of being negative (median = − 0.73, 90% CI [− 1.36, − 0.18]). It is thus possible that a quadratic relationship exists between mind wandering reported a posteriori and the amount of Remember responses (Fig. 3).

We then fitted a mixed Bayesian logistic model (with participants and items as random effects) to predict the probability of giving either a Remember or a Know answer after correctly recognizing an item, based on the mind wandering level reported at encoding. The model had an explanatory power ($R^2$) of about 26.4%. Within this model, it appears that the quadratic trend had a probability of 96.68% of being negative (median = -5.44, 90% CI [− 11.10, − 0.7]). It is thus possible that a quadratic relationship exists between the mind wandering level at encoding and the state of consciousness associated with recognition. As shown in Fig. 4, the probability of realizing a recollection-based recognition (R answer) decreases if the attentional level at encoding either drops below the median or rise above, following the same reversed U-shaped pattern as in Fig. 3. Thus, the highest probability of experiencing the recollection of an item previously seen lies when the attentional focus at encoding is around the median value.

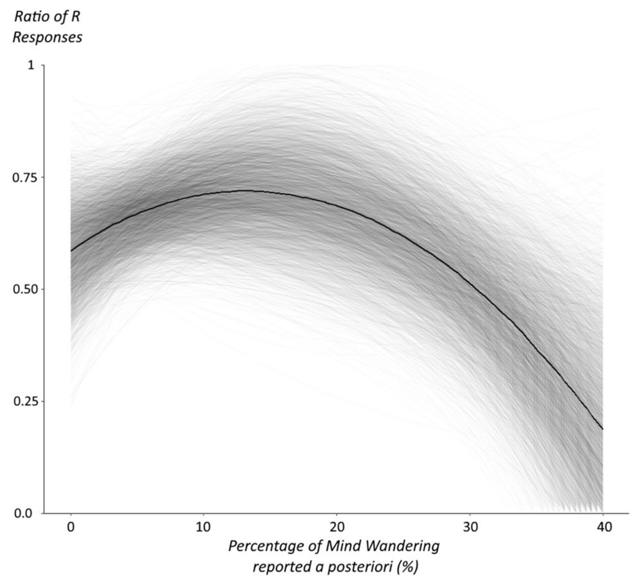


**Fig. 3** Prediction of R responses ratio based on the mind wandering reported a posteriori. The bold line represents the median effect of the a posteriori mind wandering on recognition type. The thin lines correspond to all possible effects based on the 4000 draws from the posterior distribution

No significant results were found concerning the prediction of contextual information (spatial and temporal) with both *online* and a posteriori probes (see supplementary material section for a complete description of the models).

## Discussion

The goal of this study was to systematically assess the influence of mind wandering on episodic memory encoding in an ecological setting. First, we found that the propensity of mind wandering reported a posteriori negatively predicts recognition. Second, we found that both the a posteriori reported mind wandering and the *online* mind wandering scores predict the probability of obtaining a Remember answer following a quadratic, reversed U-shaped trend.

Previous studies have shown that perturbations of attention during encoding hinder memory formation, both in divided attention paradigms (Craik et al., 1996; Fernandes & Moscovitch, 2000; Jennings & Jacoby, 1993) or during episodes of mind wandering (Seibert & Ellis, 1991; Smallwood, Davies, et al., 2004, Smallwood, O'Connor, et al., 2004). Some of our results replicate these findings, as the mind wandering reported a posteriori appeared to be a predictor of the ratio of correctly recognized items. The hindering effect of mind wandering on encoding processes may be

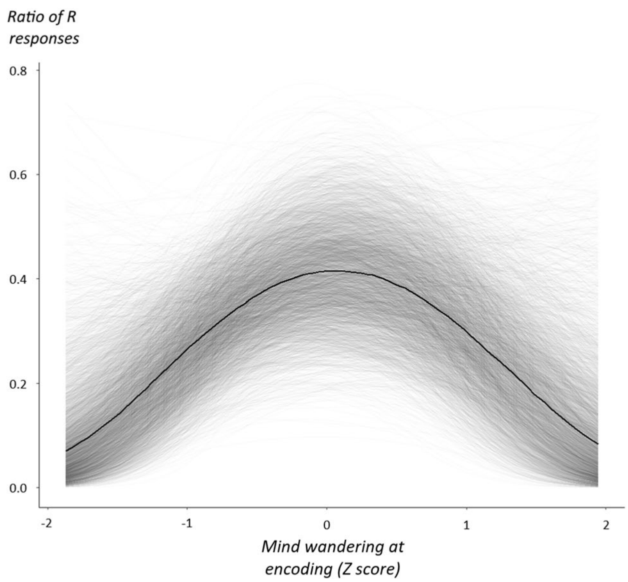


**Fig. 4** Probability of obtaining a Know (0) vs Remember (1) response predicted by mind wandering level at encoding. The bold line represents the median effect of mind wandering on recognition type. The thin lines correspond to all possible effects based on the 4000 draws from the posterior distribution

a consequence of the perceptual decoupling occurring when task-unrelated thoughts are experienced (Baird, Smallwood, Lutz, & Schooler, 2014; Barron, Riby, Greer, & Smallwood, 2011; Smallwood & Schooler, 2006). Perceptual decoupling corresponds to a shift of attention from the task at hand toward internally generated thoughts. It can be interpreted as a state of divided attention between the external and internal environments. Thus, participants reporting a high level of mind wandering during the navigation are likely to have experienced episodes of decoupled attention and these episodes led to a hindering effect on scenes encoding reflected in subsequent recognition. However, when considering the measures reported *online* during navigation, our results did not replicate the previous findings about the effect of mind wandering on memory. While there is a discrepancy in our two main measures' significance, the relationship between mind wandering at encoding and subsequent memory remains negative, which is in line with the literature. It is possible that the criterion used by our participants to determinate if they were experiencing mind wandering when performing the task was less precise than the one they used when completing the final probe, which distinguish thoughts based on task-relatedness and stimulus dependency.

At first, we hypothesized a negative linear relationship between mind wandering and the probability of having a Remember response (reviving the scene within its spatio-temporal context): the more the mind wandering at encoding increases, the less likely the subsequent recognition is to be a Remember response, as mind wandering seems to decrease the propensity of recollection-based recognitions (Riby et al., 2008). However, our results suggest a slightly more complex scenario. Indeed, the relationship between mind wandering (both *online* and a posteriori) and the probability of giving a Remember response followed a quadratic trend corresponding to a reversed U-shape curve. The probability of producing a Remember response is higher when the participant presents a medium level of mind wandering: neither too focused on the task, nor on internal thoughts. The fact that a high level of mind wandering predicts a lower rate of Remember responses is coherent with the literature and can be explained by the decoupling attention hypothesis previously described (Riby et al., 2008; Smallwood & Schooler, 2006). Indeed, being in a state of perceptual decoupling decreases the availability of cognitive resources and could prevent from engaging in a complex processing of the information that would allow the binding of the item with its context. Thus, if the item is later recognized, it is more likely to be on the basis of familiarity, without a reviviscence of the event in its specific context (and thus, producing a Know response). However, the fact that a high focus on the environment (thus associated with a low level of mind wandering) leads to a lower probability of obtaining Remember responses is a result seemingly at odds with previous findings.

Contrary to most previous studies, the encoding phase in the present work took place during the navigation in a complex environment. Moreover, as we used an incidental encoding paradigm, the critical items were not specifically distinct from the rest of the environment. Thus, when participants reported a high level of concentration on the environment, this may indicate a high focus on some parts of the environment, probably on spatial details such as their trajectory or the cues needed to continue their navigation. In other words, their attention could have been narrowed on some stimulus of interest. The narrowing of the attentional focus is known to prevent influence from distractors (LaBerge, Brown, Carter, Bash, & Hartley, 1991) as focusing on a visual cue imply inhibiting the processing of concurrent cues (Facoetti & Molteni, 2000). Thus, being too focused in a complex environment may lead to a better processing of some salient stimuli but a worsened processing of other elements in the environment. A stimulus outside the participant's attentional focus, processed shallowly, is then more likely to be recognized on the basis of familiarity (hence, associated with a Know response). Thus, for a participant to have the highest probability to recognize a scene in a complex environment on the basis of recollection, it seems it is better to have an opened attentional focus: neither too engaged in mind wandering nor too focused on the environment.

This attentional explanation, however, does not account for the lack of significant relationship between context memory and mind wandering. An alternative hypothesis would be that experiencing a medium level of mind wandering would allow the participant to remember an event based on associated thoughts. Indeed, thoughts experienced during an event are not dissociated from the event itself and are encoded as part of the experience (Jeunehomme, Folville, Stawarczyk, Van der Linden, & D'Argembeau, 2018; Stawarczyk & D'Argembeau, 2019; Stawarczyk, Jeunehomme, & D'Argembeau, 2018). Thus, producing an R response may also rely on remembering the internal thoughts experienced during an event. Being in a state of stimulus-related mind wandering has already been shown to improve encoding (Maillet & Schacter, 2016; Maillet, Seli, & Schacter, 2017). It is possible that, when trying to remember a scene, recollective processes can be used more easily if stimulus-related thoughts were experienced during the presentation of the scene, as it provides additional elements to bind the scene with. This would explain why mind wandering was not found to be associated with contextual memory while being associated to the occurrence of R answers. Experiencing no mind wandering at all would not provide benefits for the remembrance of the scenes, while experiencing too much mind wandering would not allow for a proper binding between the thoughts and the scenes. However, these potential explanations are purely speculative, as we did not have a way to check how our participants distributed their attention across the environment or what the content of their mind wandering was. Further studies using either VR or basic stimuli (such as words or images) coupled with eye tracking could be done in order to test the "narrowing of attention" hypothesis, while the "memory for thoughts" hypothesis could be tested by exploring the content of mind wandering with additional thought probes.

One main concern about our experimental design is the low number of both critical items and thought probes. While it makes sense to have few thought probes in the virtual environment – as it could hinder the ecological purpose of a virtual reality design – this leads to a very low rate of recognized items, as one item is needed for each thought probe. This is especially true as we used an incidental encoding paradigm, known to produce less responses than a voluntary encoding task, even in a virtual environment (Plancher et al., 2010). Moreover, the mean attentional score reported with the thought probes was mostly directed toward the environment. Thus, participants were not experiencing much mind wandering in this study. As a virtual reality design is an immersive and somewhat enjoyable paradigm, it could have led to a better task engagement, a greater interest toward the environment, and thus a reduced mind wandering propensity. As boredom can be seen as one of the major predictors of mind wandering (Bench & Lench, 2013; Danckert, 2018; Eastwood, Frischen, Fenske, & Smilek, 2012; Hunter & Eastwood, 2018; Malkovsky, Merrifield, Goldberg, & Danckert, 2012; Seli, Carriere, & Smilek, 2015), it would make sense, when studying mind wandering, to induce it through a boring, simple and repetitive task. Moreover, the use of an explicit online measure of mind wandering (thought probes) may not be the optimal way to assess variations of attention. Implicit measures of mind wandering such as pupil dilation (Franklin, Broadway, Mrazek, Smallwood, & Schooler, 2013; Grandchamp, Braboszcz, & Delorme, 2014; Kang, Huffer, & Wheatley, 2014; J. Smallwood et al., 2011), blink frequency (Smilek, Carriere, & Cheyne, 2010), electrodermal activity (Smallwood, Davies, et al., 2004; Smallwood, O'Connor, et al., 2004; Smallwood et al., 2007) or reaction time (Foulsham, Farley, & Kingstone, 2013; Franklin, Smallwood, & Schooler, 2011) may be best suited to test online variations of attention, especially if they are coupled with neuroimaging measures (for a review, see Martinon, Smallwood, McGann, Hamilton, & Riby, 2019). However, the specificity of such indices and their possible use to assess the effect of attention variation on memory encoding is yet to be tested and should be the focus of a future study.

## Conclusion

The present study proposes a novel way to test the influence of spontaneous variations of attention on episodic memory encoding. By using a virtual reality paradigm coupled with both *online* and a posteriori explicit measures of mind wandering, we showed that the relationship between mind wandering level at encoding and the state of consciousness associated with subsequent recognition followed a reversed U-shaped pattern: both a low and a high degree of mind wandering predict a higher rate of familiarity-based recognition, while the highest probability of realizing a recollection-based recognition lies in the middle. This result contrasts with previous findings suggesting that a low degree of mind wandering would predict a high rate of recollections. This relationship may thus be a more ecological representation of the relationship between attention and memory.

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**Data availability** The descriptive data and statistical models of this study can be found in the "Supplementary material" section. This study was not pre-registered. Raw data and scripts for statistical analyses would be made available on request.

### Compliance with ethical standards

**Conflict of interest** The authors have no conflict of interest.

**Ethical approval** The manuscript does not contain clinical studies or patient data.

**Informed consent** All participants signed an informed consent before participating in this experiment.

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