

RESEARCH ARTICLE

The Impact of Exposure to a Novel Virtual Environment on Episodic Memory as a Function of the Level of Processing During Encoding

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ABSTRACT

This study examines whether exploring a novel environment in virtual reality enhances verbal episodic memory as a function of level of processing during encoding. Thirty-four participants completed three sessions. In the first, they familiarized themselves with a virtual environment. In the second and third sessions, they explored either the same (familiar) or a different (novel) environment before completing an episodic memory task. The task required participants to encode words under deep or shallow conditions and then complete free recall and recognition memory tests. Results showed that recall and recognition were better with deep encoding compared to shallow encoding. Recall was better in the second session for deep encoding, regardless of novelty. For shallow encoding, recall was better after exploring the novel environment, but only if it occurred in the third session. Recognition memory was unaffected by novelty. These findings suggest that environmental novelty benefits weak memories, but under specific conditions.

1 | Introduction

Attention to novelty—that is, directing the senses toward what is unknown—is a hallmark of human and animal behavior; it is adaptive, as novelty in the environment may signal threat, danger, or reward (Panksepp 1998). In the literature, a distinction is made between different types of novelty (i.e., absolute novelty, contextual novelty, associative novelty, environmental novelty) that lead to different brain responses and involve the synthesis and release of various neurotransmitters (norepinephrine, dopamine, and acetylcholine) (Duzel et al. 2010; Kafkas

and Montaldi 2018; Lisman and Grace 2005; Schomaker and Meeter 2015).

Almost a century ago, novelty already was shown to promote memory at the stimulus level (Von Restorff 1933). In this seminal work, it was shown that information presented in a distinct font is remembered better than information presented in a monotonous or standard font. This effect became known as the von Restorff or isolation effect (Hunt 1995), and has been attributed to the distinctiveness of the material (Schmidt et al. 2021; Schmidt and Schmidt 2017), and not to the perceptual salience

of the material per se (Dunlosky et al. 2000), nor to attention during encoding (Bireta and Mazzei 2016). In the current study, however, we will focus on environmental novelty (i.e., novelty of a place where one has never been before).

Among its effects on cognition and behavior, novelty is thought to elicit a learning signal such that the novelty of a stimulus promotes learning (Tulving and Kroll 1995). The underlying neural mechanisms by which environmental novelty and episodic memory interact have been described in influential theoretical models building on animal studies (Duzel et al. 2010; Lisman and Grace 2005; Schomaker and Meeter 2015). These models suggest that a loop between the hippocampus and the ventral tegmental area (VTA) facilitates encoding of new information. The general idea is that the CA1 region of the hippocampus compares predictions made through the tri-synaptic and CA3 pathways to the hippocampus and sensory reality arriving to CA1 through the monosynaptic direct pathway. In the case of a novel event, a novelty signal activates the VTA through the accumbens nucleus and ventral pallidum. The VTA in turn activates dopamine release in CA1 facilitating late long-term potentiation (LTP) for several minutes, thus promoting encoding of novel information into long-term episodic memory. This has notable effects on episodic memory by strengthening encoding and consolidation processes of the novel environment itself, but also of other information encountered just before or several minutes after the novel experience. In contrast with the work that has shown that distinct information is remembered better, as in the von Restorff and isolation effect (Hunt 1995; Schmidt and Schmidt 2017; Von Restorff 1933), this involves generalizable memory effects not limited to the novel experience itself.

While studies in rodents have shown that exposure to a novel environment significantly improves episodic memory encoding and consolidation in tasks performed after the novel experience (Davis et al. 2004; Li et al. 2003), the boosting effect of environmental novelty exposure on episodic memory in humans remains controversial. Some studies reported a beneficial effect of novelty on episodic memory. For instance, Fenker et al. (2008) presented new or familiar images of scenes to participants and then evaluated episodic memory on a word learning task via free recall and recognition tests. In the recognition test, recollection versus familiarity processes were estimated with the Remember/Know paradigm (Gardiner et al. 1996). The results showed that participants achieved higher free recall and recollection (but not familiarity) scores when exposed to new images shortly before the encoding task compared to participants exposed to familiar images. Additionally, in a within-subjects design using virtual reality (VR), Schomaker et al. (2014) observed enhancement of verbal free recall but not recognition after participants explored a novel rather than familiar virtual environment. In a similar study, the positive impact of exposure to a novel spatial environment on episodic memory was observed only after active exploration but not passive exploration (Schomaker and Wittmann 2021). In the same vein, students attending a new course 1 h before storytelling (Ballarini et al. 2013) or before learning a novel geometric shape (Ramirez Butavand et al. 2020) scored better on subsequent story or shape memory tests than those attending a familiar, previously attended lesson. These studies support that exposure to novel materials promotes subsequent encoding and recall (and recollection) of verbal and visual information. Of note, studies that included measures of familiarity-based recognition did not find facilitatory effects of

novelty on this type of memory (Fenker et al. 2008; Schomaker et al. 2014).

In contrast, other studies did not find any effect of environmental novelty on episodic memory. Quent and Henson (2022) investigated the retroactive effect of exposure to a novel virtual environment on episodic memory by showing words to encode immediately before exposure to novel or familiar immersive environments. They found no effect of the novelty of the environment on free recall or recognition memory performance. Moreover, Biel and Bunzeck (2019) examined the effect of novelty on recollection and familiarity-based recognition memory by exposing participants to short film sequences either 15 min before encoding a list of words, 15 min after encoding the words, or immediately after encoding the list of words. In neither case did they find a beneficial effect of novelty on recollection and familiarity scores.

These discrepancies in findings may be explained by differences in experimental designs (e.g., timing, population or type of novelty exposure) (Lorents et al. 2023). However, additional studies are necessary to identify the specific conditions under which novelty can promote episodic memory. In the current study, we assessed whether the strength of the initial episodic memory trace is a factor that influences whether novelty promotes subsequent episodic memory. Indeed, it has been suggested that the hippocampus-VTA loop triggered by the presence of novelty that theoretical models describe (Duzel et al. 2010; Lisman and Grace 2005; Schomaker and Meeter 2015) has different consequences as a function of the initial processing of information during its encoding. More specifically, it has been proposed that memories that would usually be forgotten particularly benefit from enhanced LTP induced by the dopamine release into the hippocampus (Duszkiewicz et al. 2019; Moncada and Viola 2007). Without such synaptic plasticity, weaker memory traces of some events would not be consolidated. But the dopamine release and hippocampal activation due to novelty transform initially weak memory traces into long-lasting stable memories. In contrast, memory traces that are strong from the start would not require more synaptic plasticity to be maintained and would be less affected by novelty. This led to the prediction that the enhancing effect of novelty on episodic memory encoding and consolidation should be greater for weak than for strong memories.

Two previous studies (Quent and Henson 2022; Schomaker et al. 2022) assessed this idea in humans using a level of processing manipulation during the encoding of words, as deep encoding leads to more robust and long-lasting memories than shallow encoding (Craik and Lockhart 1972). Quent and Henson (2022) failed to show any effect of novelty on episodic memory for words immediately encoded before exposure to novel versus familiar VR environments, whether deeply or shallowly processed. Using a between-subjects design, Schomaker et al. (2022) found better recall after exposure to a novel VR environment than after exposure to a familiar VR environment in younger (but not older) adults, with no differential effect due to levels of processing.

The goal of the current study was to further test the hypothesis that exposure to environmental novelty enhances recall of words encoded with shallow processing more than words encoded

with deep processing by adapting the experimental design by Schomaker et al. (2014) using a level of processing manipulation. Concretely, using a within-subjects design and an immersive VR system allowing for active exploration, participants first familiarized themselves with a virtual environment (Session 1) and subsequently explored either the familiar or a novel environment (Sessions 2 and 3; order counterbalanced between participants) for 5 min. After each exploration, they were presented with a list of words, with one block studied under shallow encoding instructions and another studied under deep encoding instructions in a within-subjects design. Then, participants completed a free recall task followed by a recognition memory task using the Remember/Know paradigm (Gardiner et al. 1996; Tulving 1985). While the effects were mainly expected to be observed on free recall as reported in previous studies (Schomaker et al. 2022, 2014; Schomaker and Wittmann 2021), we added an assessment of recollection and familiarity with the Remember/Know paradigm as the study by Fenker et al. (2008) indicated that recollection, but not familiarity, can also be enhanced by exposure to novelty.

The primary hypothesis was that exposure to novelty would impact words encoded with deep processing and words encoded with shallow processing differentially. According to the level of processing theory (Craik and Lockhart 1972), episodic memory performance should be better for words after deep encoding than after shallow encoding, thus creating respectively strong and weak memory traces. Following the theoretical proposal by Duszkievicz et al. (2019), if novelty promotes memory for weak more than strong memory traces, one should observe better recall (and recollection) of shallowly encoded words after exploration of the novel virtual environment than after exploration of the familiar virtual environment, but a smaller or no benefit for deeply encoded words.

Of note, the order of the sessions has sometimes been found to influence episodic memory performance. Whereas this did not affect recall score in the original study (Schomaker et al. 2014), Schomaker and Wittmann (2021) observed that recall performance was higher when participants explored a novel environment on Session 2 than on Session 3, potentially due to the additional factor of the novelty of the VR experience, which might wear off over sessions. Therefore, even though the order of presentation of familiar and novel environments was counterbalanced across participants, order was analyzed as a variable of interest.

Additionally, participants completed some questionnaires related to personality and their subjective experience during exploration. One important factor that may contribute to the beneficial effect of immersive VR on memory is the feeling of presence (i.e., the sense of being there). Some studies indicated that a higher degree of presence is associated with better memory performance for stimuli presented in virtual or immersive 3D environments (Cadet and Chainay 2020; Makowski et al. 2017). This is interpreted as presence improving the selective orientation of attention to stimuli, thus facilitating their encoding (Makowski et al. 2017). But other studies failed to report improved memory for information learned during immersive VR associated with a high sense of presence compared to other displays inducing less presence (Buttussi and Chittaro 2018; Green et al. 2025) or

did not find an association between presence ratings and memory (Smith and Mulligan 2021). Some studies even showed that enhanced presence in VR is linked with poorer memory for materials presented during VR (Chen and Yao 2021). While these studies focused on memory for materials pertaining to the VR environment itself, very few experiments assessed whether the feeling of being immersed in the virtual environment promotes the beneficial effect of novelty on subsequent episodic memory. In Schomaker et al. (2014), presence was higher after exploring the novel environment than the familiar one. Also, free recall of words was better for subjects with high presence scores than for subjects with low presence scores. But the difference in presence between novel versus familiar exploration was not related to the recall benefit due to novelty. In Schomaker and Wittmann (2021), presence did not correlate with recall on the memory test that followed exploration of a familiar or novel VR environment. More recently, in a study comparing recall in a memory task performed after either experiencing a VR exploration or watching a documentary, memory was found to be enhanced after the VR experience, and VR exploration was associated with higher presence than watching the documentary, but presence was not a predictor of the memory benefit due to VR exploration (Servais and Bastin 2025). Therefore, to further explore the influence of novelty exposure on the feeling of presence and its potential link with memory scores, in the current study, participants completed the Igroup Presence Questionnaire (IPQ) after each exploration.

As individuals have different tendencies to seek out and appreciate novelty (Cloninger 1986), and because the strength of the effects of novelty on episodic memory may depend on these individual characteristics (Krebs et al. 2009), we used the NEO Personality Inventory (NEOPI) to assess the openness to experience dimension as a proxy of curiosity and the novelty seeking subpart of the Temperament and Character Inventory-Revised (TCI-R) personality questionnaire to assess the tendency toward exploration of participants. This allowed us to test whether individuals with low novelty seeking and curiosity scores would show better free recall performance following exploration of a novel rather than a familiar environment.

Finally, because active exploration of an environment may be an important factor in generating a novelty effect and because exposure to novelty (and the resultant release of dopamine) is predicted to improve motivation to explore virtual environments (Schomaker and Wittmann 2021), we computed the distance traveled by the participant in each environment, as previously done by Schomaker et al. (2022), in order to assess the difference in distance as a function of the novelty of the environment and the possible link with memory performance.

2 | Methods

2.1 | Participants

The sample size was determined via a priori power analyses using G*Power 3 (Faul et al. 2007). A minimum of 34 participants is required to observe the main effect of novelty with the same effect size as in Schomaker et al. (2014) ($f=0.43$, $\alpha<0.05$, power=0.80). A sample of 24 participants is needed to be able



FIGURE 1 | Experimental design. This diagram shows the different orders by which participants could explore the different environments (Alien or Island) over Sessions (1–3) as counterbalanced over participants (rows).

to observe an a priori medium-size within-factor interaction between novelty condition and level of processing ($f=0.25$) for an $\alpha<0.05$ and a power of 0.80. A total of 24 participants is required to observe a medium-size within-between interaction between novelty condition, order of presentation of the environments, and level of processing ($f=0.25$) for an $\alpha<0.05$ and a power of 0.80.

Thirty-six participants (11 men, 25 women), aged 18 to 30 years old (mean age = 22.08 ± 2.96 years) and naive to our study's purpose, participated in the experiment. They were all native French speakers, and none reported any known past or current neurological or psychiatric disorders during a screening interview. For a comfortable VR experience, an additional inclusion criterion was good visual acuity without the need for glasses or contact lenses. Of the 36 participants enrolled, one dropped out due to illness, and one was excluded due to a score above 40 on the cybersickness questionnaire (see below). Our final sample, therefore, included 34 participants (11 men and 23 women). Data were collected in May and June 2022.

This study was performed in line with the principles of the Declaration of Helsinki. The study was approved by the ethics committee of the Faculty of Psychology of the University of Liège (No. 1920-110). All participants signed a written informed consent before participating in the experiments. Participants were asked whether they were used to playing video games and/or to using VR devices (yes/no answer in a single question).

2.2 | Materials

Participants explored two virtual environments: an “Alien” environment and an “Island” environment (see Figure 1 for the experimental design). The “Alien” environment included unusual plants, spaceships, and metallic structures predominantly in shades of gray and pink. The “Island” environment depicted meadows with trees, small houses, and statues and was predominantly shaded green. The environments were created with Unity 2018.4.6f1 and were matched in terms of size, as well as position and number of objects. Both environments were presented using a Titan MSI computer equipped with an NVIDIA GeForce GTX 1070 8GB VRAM graphics card and an Oculus Rift S headset and its associated Touch Bundle controllers.

Two recall/recognition memory tasks ran on the PsychoPy software (Peirce et al. 2019). For this aim, we selected eight lists of 20 French 2- to 8-letter words from the database of lists of semantically related words by Dubois and Poitou (2002). Each list included the same number of words from different semantic categories (e.g., animals, food, objects). The eight lists were matched in terms of word length (number of letters, $F(7, 152)=0.05$, $p=0.99$) and in terms of frequency in movies obtained from Lexique (New et al. 2004), $F(7, 152)=0.001$, $p=1$. For the encoding phase of each task, two lists served to create a block with an instruction for deep encoding and a block with an instruction for shallow encoding (see below). For the recognition memory phase of each task, four lists of 20 words were used: the two lists of 20 words previously shown for encoding plus two

lists of 20 words that subjects have never seen. The attribution of each list to the two memory tasks and to the target versus distractor lists was counterbalanced across participants, resulting in a total of 8 versions.

The materials also included several paper-and-pencil questionnaires. To assess the subjective experience of spatial presence, the involvement in the virtual environment, and its realism, participants were asked to complete the IPQ. More specifically, we used a French version of the IPQ validated by the Laboratoire de Cyberpsychologie de l'UQO, which indicated that the scale has a good internal consistency (Cronbach $\alpha = 0.84$) (Robillard et al. 2002). In addition, to examine how well they tolerated the VR experience (nausea, dizziness, headaches), they completed a cybersickness questionnaire (Cyberpsychology Laboratory of the Universit   du Qu  bec, Outaouais) validated in French by Bouchard et al. (2021). Participants with a score higher than 40 out of 64 (corresponding to reports of feeling unwell) were not included in the subsequent sessions. We excluded only one participant because of cybersickness. To assess personality dimensions related to novelty processing, we used the TCI-R section that allows for evaluating individuals' tendency to seek novelty (using a French version validated on a French-speaking Belgian sample by Hansenne et al. (2005)) and the section of the NEO-PI that allows inferring their degree of curiosity (whose psychometric properties for the French version has been validated by Rolland et al. 1998).

2.3 | Procedure

Each participant took part in three sessions of 30 min each, with a pace of one session per day over 3–5 days. Each participant was tested individually in a lab room where the VR set was installed for the entire study. For the VR exploration, the participant stood in the middle of an area of around 9 m² defined in Oculus based on two sensors placed on each side of the computer. They wore the headset to be immersed in the environment and used the joystick of the right-hand Touch Bundle controller to move smoothly in all directions within the environment. For each virtual environment exploration, we calculated the total distance traveled (in Unity meters) as the sum of Euclidean distances between successive data points (2D). Besides the VR exploration, participants completed memory tasks and questionnaires in the same room while sitting at a table.

2.3.1 | Session 1 (Familiarization With a Virtual Environment—Fa)

During the first session, participants explored and became familiar with either the "Alien" environment or the "Island" environment. Participants were first instructed how to navigate the virtual environment using the joystick. Then, they were allowed to explore the environment for 5 min, which was sufficient to explore it exhaustively. In previous studies, exploration time was between 3 and 5 min (Schomaker et al. 2022, 2014; Schomaker and Wittmann 2021). After the exploration, participants were asked to complete the IPQ and the cybersickness questionnaire.

2.3.2 | Session 2 (Virtual Environment Exploration and Memory)

In Session 2, participants started by exploring either the same environment as in Session 1 (familiar environment [F]) or the other environment (novel environment [N]) for 5 min. Then, they completed an episodic memory task and some questionnaires.

During the encoding phase of the memory task, a list of 40 words was presented in two blocks of 20 words. Each of the 40 words was shown for 2 s, with an interval of 1 s between each word, during which a central fixation cross was displayed. In one block, participants performed a *deep encoding* task, during which they determined whether the word on the screen was pleasant (press "v") or not (press "n"). In the other *shallow encoding* block, participants determined whether the word shown on the screen included at least two e's (press "v") or not (press "n"). The order of the encoding type blocks was counterbalanced across participants.

At the end of the encoding phase, the participants completed the IPQ to rate their experience with exploring the virtual environment at the beginning of the session. The questionnaire, which took around 3 min to be completed, acted as a distracting task preventing rehearsal of the words. Participants then had to recall aloud the words from the encoding task that they remembered. There was no time limit, but participants spontaneously completed recall in less than 2 min. The experimenter took note of the words. Next, participants completed a recognition memory task. Eighty words, consisting of 40 words seen during the encoding phase mixed with 40 new words, were presented to the participants. For each word, they had to indicate whether it was presented during the encoding phase ("old"; press "v") or not ("new"; press "n"). Participants had 5 s to give their answer. For each "yes" answer, participants determined if they recognized the words based on (1) remembering details of the encoding context (recollection) ("1" key), (2) knowing (familiarity for the words without recollection of details) ("2" key), or (3) if they were unsure of the word's presence in the previous task (guess) ("3" key). Participants had 5 s to give their answer. The time limit was added to equate the delay between encoding and recognition of the words as much as possible across participants.

At the end of the session, participants completed either the TCI-R or the NEO-PI.

2.3.3 | Session 3 (Virtual Environment Exploration and Memory)

In Session 3, participants first explored the other virtual environment for 5 min, which was either the novel environment (N) or the environment of Session 1 (familiar environment [F]), depending on counterbalancing. Then, they completed the memory task, with the same procedure as in Session 2, but with a different list of words. Finally, they were asked to answer the personality questionnaire (TCI-R or NEO-PI depending on the one given in Session 2).

2.3.4 | Counterbalancing

At the end of Session 1, which was the first exploration round, the environment visited was considered “familiar” (F). Participants would explore the same environment a second time in Session 2 or 3. The other environment, which the participants had never explored, was considered “novel” (N); this environment was explored only once by participants, either in Sessions 2 or 3. The order of presentation of the environments (novel; familiar) across the three sessions varied as follows: familiarization, familiar, novel (Fa/F/N) or familiarization, novel, familiar (Fa/N/F). These two orders of presentation and the attribution of each environment (Alien vs. Island) to the conditions were equally distributed among all participants (see Figure 1) in a counterbalanced fashion.

2.4 | Statistical Analyses

2.4.1 | Memory Tasks

The scores in the free recall task were the proportion of words correctly recalled according to whether they were encoded deeply or shallowly. As participants produced very few intrusions (median number in the familiar condition = 0.5, and in the novel condition = 0), intrusions were not analyzed. For the recognition memory task, because it followed the recall task, performance may be driven by recalled words (which are also likely to be recollected). Therefore, we computed recognition memory performance only for target words that participants did not recall. Global recognition performance was obtained with hits (the proportion of correctly recognized nonrecalled *old* words) minus false alarms (the proportion of *new* words identified as old by participants) for deep and shallow encoding conditions. For Remember/Know, we calculated dual-process signal detection model estimates of recollection ($[\text{proportion of Remember responses to hits} - \text{proportion of Remember responses to false recognitions}] / [1 - \text{proportion of remember responses to false recognitions}]$) (Yonelinas et al. 1996) and familiarity (d-prime based on the independent Remember/Know procedure, where the familiarity score for hits and false recognitions is given by the proportion of Know responses/ $[1 - \text{proportion of Remember responses}]$) (Jacoby et al. 1997). These estimates provide a measure of accuracy for the contribution of recollection and familiarity to recognition decisions. Proportions of Guess responses were not analyzed as they were too rare. For each of these scores, we computed a repeated-measures $2 \times 2 \times 2$ ANOVA with the novelty condition (exploration of familiar vs. novel environment before the task) and the type of encoding (deep/shallow) as within-subject factors, and the order of presentation of the environments (F/N or N/F) as a between-subject factor. The analysis of recognition memory data when considering all items (those that were recalled as well as those that were not) can be found in [Supporting Information](#).

Additionally, to investigate evidence in favor of null effects, we also computed the Bayesian version of the repeated measures ANOVAs. We report the BF Inclusion (BFInc), which is a comparison of all models that include the factor(s) to all models that do not include the factor(s) (Rouder et al. 2012). As a rule of

thumb (Quintana and Williams 2018), values between 3 and 10 or between 0.33 and 0.10 are interpreted as moderate evidence for the alternative model and the null model, respectively, while values above 10 or below 0.10 are considered strong evidence for the alternative model and the null model, respectively. Values between 0.33 and 3 represent only anecdotal evidence. We will only discuss effects that received moderate to strong evidence.

2.4.2 | Exploration Behavior

The distances traveled by participants during the exploration of the virtual environments were compared using a 2×2 repeated-measures ANOVA with the exploration round (Fa, N, or F environment) as a within-subject factor, and the order of presentation of the environments in Sessions 2 and 3 (N/F or F/N) as a between-subject factor. Moreover, we performed Pearson correlations between the distance traveled during the exploration of the novel virtual environment (and also the difference between distance traveled in the novel and familiar environment as an index of how much novelty induced a bonus of exploration) and a score reflecting novelty-related memory benefit (calculated as free recall scores following the N environment minus free recall scores following the F environment, divided by the sum of the two scores) for deeply encoded words and shallowly encoded words, separately.

2.4.3 | Questionnaires

For presence scores, we compared the scores of the IPQ questionnaires after exploration of a familiar versus a novel environment, using a paired Student's *t* test.

Also, we tested whether the novelty-related memory benefit for deep and shallow encoded words was associated with certain personality traits (curiosity as inferred from NEOPI and novelty seeking from the TCI-R questionnaire) and with a difference in presence experienced in the novel and the familiar environment (as measured by the IPQ) using Pearson correlations.

Finally, we analyzed whether participants' previous experience with VR and/or video games affected our results. To this end, participants were divided into two groups according to whether they reported being used to VR and/or video games (Yes or No). The novelty-related memory benefit scores were compared between these two groups with an independent-samples *t* test.

3 | Results

The dataset from the current study is available on <https://osf.io/f3aps/>.

3.1 | Memory Tasks

Mean free recall and recognition memory scores as a function of the novelty of exposure (F, familiar or N, novel), the type of encoding (deep or shallow), and the order of presentation of the environments (F/N or N/F) are presented in Table 1.

3.1.1 | Recall

The ANOVA on the proportion of words correctly recalled by participants according to the novelty of exposure (F or N), the type of encoding (deep or shallow), and the order of presentation of the environments (F/N or N/F) revealed no main effect of novelty on free recall, $F(1,32)=2.93$, $\eta_p^2=0.08$, $p=0.09$, $BFInc=0.31$. There was a main effect of the type of encoding, $F(1,32)=63.27$, $\eta_p^2=0.66$, $p<0.001$, $BFInc=1.58^{e+12}$, indicating that free recall was significantly better for deeply encoded words compared to shallowly encoded words. The main effect of the order reached significance but received anecdotal evidence, $F(1, 32)=4.51$, $\eta_p^2=0.12$, $p=0.04$, $BFInc=1.12$. The interaction between the novelty of exposure and the order of presentation of the environments was significant, with higher performance in the condition that participants performed first (F in the F/N order and N in the N/F order), but with anecdotal evidence, $F(1,32)=6.81$, $\eta_p^2=0.17$, $p=0.01$, $BFInc=1.15$. The triple interaction between novelty, the type of encoding, and the presentation order was also significant and received strong evidence, $F(1,32)=30.43$, $\eta_p^2=0.48$, $p<0.001$, $BFInc=16771.63$ (Figure 2). No other interaction was significant; all F 's < 1 .

TABLE 1 | Mean free recall and recognition memory (hits for nonrecalled items-false alarms) scores.

	Familiar condition		Novel condition	
	Deep	Shallow	Deep	Shallow
Free recall				
F/N	0.30 (0.13)	0.08 (0.04)	0.22 (0.13)	0.15 (0.08)
N/F	0.15 (0.08)	0.10 (0.05)	0.26 (0.07)	0.08 (0.07)
Recognition				
F/N	0.77 (0.15)	0.47 (0.15)	0.77 (0.18)	0.53 (0.198)
N/F	0.77 (0.16)	0.50 (0.18)	0.77 (0.17)	0.55 (0.17)

Note: Standard deviations are in parentheses.

Abbreviations: F/N=familiar first: familiar in Session 2 and novel in Session 3; N/F=novel first: novel in Session 2 and familiar in Session 3.

To explore the three-way interaction, we ran first novelty of exposure (F or N) $\times$ order of presentation of environments (F/N or N/F) ANOVAs for deeply encoded words and shallowly encoded words separately. For words in the deep encoding condition, the main effects of novelty and order were not significant, F 's < 3.02 , p 's > 0.09 , $BFInc < 0.92$, but there was a significant novelty $\times$ order interaction, $F(1, 32)=26.89$, $\eta_p^2=0.46$, $p<0.001$, $BFInc=2611.15$. This was due to better recall in the condition that was performed in Session 2 (i.e., F for F/N order and N for N/F order) compared to Session 3. For words in the shallow encoding condition, the main effects of novelty and order were not significant, F 's < 3.31 , p 's > 0.07 , $BFInc < 1.33$, but the interaction was significant and received strong evidence, $F(1, 32)=8.59$, $\eta_p^2=0.21$, $p=0.006$, $BFInc=11.49$. In the F/N order, word recall was higher after exploration of the N environment than after the F environment, whereas no effect of the novelty of exposure on free recall existed in the N/F order.

Second, we explored the three-way interaction with novelty of exposure (F or N) $\times$ the type of encoding (deep or shallow) ANOVAs for the two orders separately. For the F/N order, there was no main effect of novelty, $F(1, 17)=0.29$, $\eta_p^2=0.01$, $p=0.59$, $BFInc=0.31$, a significant main effect of the type of encoding, $F(1, 17)=32.09$, $\eta_p^2=0.65$, $p=0.00002$, $BFInc=694.09$, and a significant novelty by type of encoding interaction, $F(1, 17)=14.50$, $\eta_p^2=0.46$, $p=0.001$, $BFInc=374.13$. The interaction was due to better memory in the F than in the N condition for deeply encoded words and better memory in the N than in the F condition for shallowly encoded words. For the N/F order, there was a main effect of novelty, $F(1, 17)=18.44$, $\eta_p^2=0.55$, $p=0.0006$, $BFInc=3.25$, a main effect of the type of encoding, $F(1, 17)=35.39$, $\eta_p^2=0.70$, $p=0.00002$, $BFInc=762.71$, qualified by a significant novelty by type of encoding interaction, $F(1, 17)=19.23$, $\eta_p^2=0.56$, $p=0.0005$, $BFInc=3101.95$. The interaction resulted from better memory in the N than in the F condition for deeply encoded words, but no difference between the conditions for the shallowly encoded words.

As these results indicate that the order of presentation of virtual environments modifies the pattern of results, we ran an additional analysis focusing only on Session 2. Proportion of

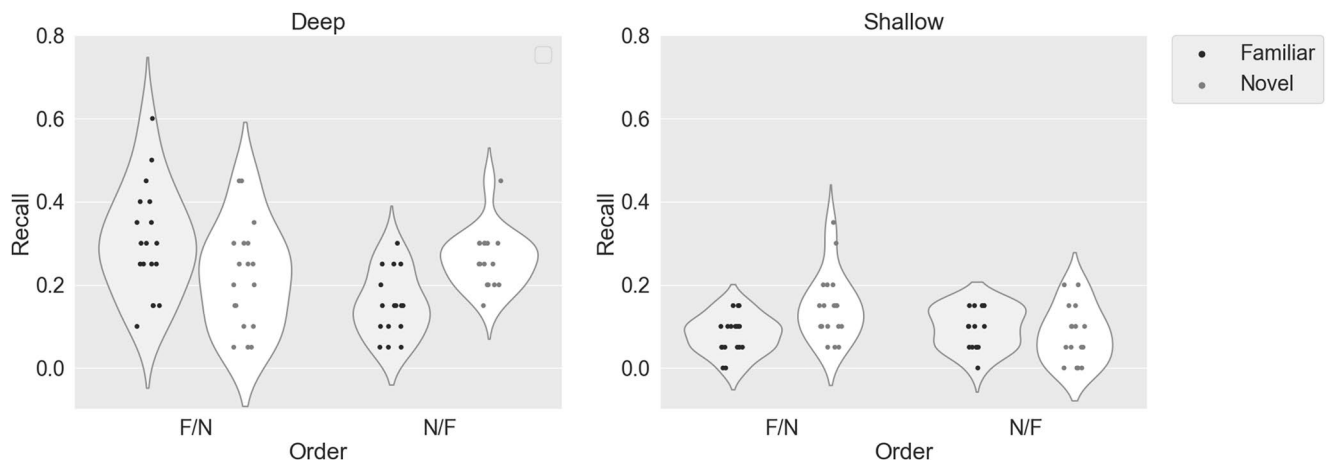


FIGURE 2 | Free recall scores as a function of the novelty of the environment explored before the memory task (familiar or novel), the type of encoding (deep or shallow), and the order of presentation of the virtual environments (F/N: familiar first; N/F: novel first).

correct recall was compared in an ANOVA as a function of the type of encoding (Deep or Shallow) as a within-subjects factor and of the novelty of the environment (Familiar or Novel) as a between-subjects factor. The results revealed a significant main effect of the type of encoding, $F(1,32)=98.18$, $\eta_p^2=0.75$, $p<0.001$, $\text{BFInc}=6.95^{\text{e}+12}$, with better recall of words after deep encoding than shallow encoding. However, there was no main effect of the novelty of the environment, $F(1,32)=0.99$, $\eta_p^2=0.03$, $p=0.32$, $\text{BFInc}=0.41$, and there was no interaction between novelty and type of encoding, $F(1,32)=1.13$, $\eta_p^2=0.03$, $p=0.29$, $\text{BFInc}=0.62$.

As an exploratory analysis, we considered the fact that the “Alien” environment may be a priori more novel in an absolute sense than the “Island” environment because its features were less likely to be encountered in everyday life. First, we compared the sense of presence and the distance traveled in the familiarization phase for the two environments. Presence score did not differ between environments, $t(32)=-0.16$, $p=0.87$, but participants explored the “Island” environment (M distance traveled = 1514, $SD=319$) more than the “Alien” environment ($M=1159$, $SD=357$), $t(32)=-3.04$, $p=0.004$. Second, because the latter results could indicate that participants did not achieve equivalent familiarization with the two environments, we tested whether the nature of the environment influenced memory performance in the different conditions by adding the environment (Island versus Alien) as a between-subject factor to the ANOVA testing the effects of novelty of exposure (F or N), the type of encoding (deep or shallow), and the order of presentation of the environments (F/N or N/F) on free recall. None of the effects involving the nature of the environment were significant (all p 's > 0.24) and the pattern of results remained as reported above.

3.1.2 | Recognition Memory

Concerning global recognition memory performance, the only significant effect was the main effect of type of encoding, which received strong evidence, $F(1,32)=92.31$, $\eta_p^2=0.74$, $p<0.001$, $\text{BFInc}=2.07^{\text{e}+8}$, showing that recognition of deeply encoded words ($M=0.77$) was better than recognition of shallowly encoded words ($M=0.51$). No other main effect or interaction was significant, all F 's < 1.52 , $\text{BFInc} < 0.32$.

Regarding recollection-based recognition memory (Table 2), the main effect of the type of encoding was significant, $F(1,32)=4.97$, $\eta_p^2=0.80$, $p<0.001$, $\text{BFInc}=5.39^{\text{e}+9}$, with strong evidence for

recollection being superior for deeply encoded words than for shallowly encoded words. No other effect or interaction was significant, all F 's < 3.26 , $\text{BFInc} < 0.76$.

Finally, for familiarity-based recognition memory (Table 2), no main effect nor interaction was significant (F 's < 0.34 , $\text{BFInc} < 0.18$), except for the main effect of type of encoding, $F(1,32)=23.09$, $\eta_p^2=0.40$, $p<0.001$, $\text{BFInc}=125.57$, due to more familiarity for words encoded with deep processing than for words encoded with shallow processing.

As for the recall data, we added the environment (Island vs. Alien) as a supplementary factor in the above-mentioned ANOVAs. The results remained the same as reported. In none of the analyses was there a significant effect or interaction involving the environment (global recognition, all p 's > 0.10 ; recollection, all p 's > 0.13 ; familiarity, all p 's > 0.36).

When the recognition memory scores were analyzed by considering all items (see [Supporting Information](#) for details), the only difference was that there was higher recollection after exploration of the N than F environment in the F/N order and higher recollection after exploration of the F than N environment in the N/F order, for words in the shallow encoding condition only.

3.1.3 | Exploration Behavior

The 2×2 repeated-measures ANOVA on distances traveled by participants during the exploration of the virtual environments with the exploration round (Fa, N, or F environment) as a within-subject factor and the order of presentation of the environments (Fa/N/F or Fa/F/N) as a between-subject factor revealed a main effect of the exploration round, $F(2,64)=17.10$, $\eta_p^2=0.35$, $p<0.001$. This effect was qualified by a significant interaction between the exploration round and the order of presentation of the environments (Fa/F/N or Fa/N/F), $F(2,64)=8.17$, $\eta_p^2=0.20$, $p<0.001$ (Figure 3). When participants experienced the environments in the order Fa/N/F, the distance traveled differed between each condition, with more distance traveled in the N environment followed by the F environment than the Fa condition (post hoc Tukey tests; $p=0.0001$ for Fa vs. F, $p=0.01$ for Fa vs. N, $p=0.04$ for F vs. N). When participants explored environments in the order Fa/F/N, there was no significant difference in terms of distance between conditions, with a marginal effect for Fa versus N ($p=0.06$; $p=0.77$ for Fa vs. F; $p=0.65$ for F vs. N). Looking at these results in terms of session order, the distance traveled tended to be longer in Session 3 than 2 than 1.

TABLE 2 | Mean estimates of the contribution of recollection and familiarity to recognition memory.

		Familiar condition		Novel condition	
		Deep	Shallow	Deep	Shallow
F/N	Recollection	0.66 (0.22)	0.15 (0.19)	0.58 (0.32)	0.20 (0.16)
	Familiarity	1.57 (1.25)	0.85 (0.55)	1.79 (2.37)	1.03 (0.73)
N/F	Recollection	0.50 (0.26)	0.20 (0.12)	0.52 (0.29)	0.17 (0.14)
	Familiarity	1.89 (0.68)	0.89 (0.47)	1.78 (1.01)	0.96 (0.41)

Note: Standard deviations are in parentheses. F/N = familiar first; N/F = novel first.

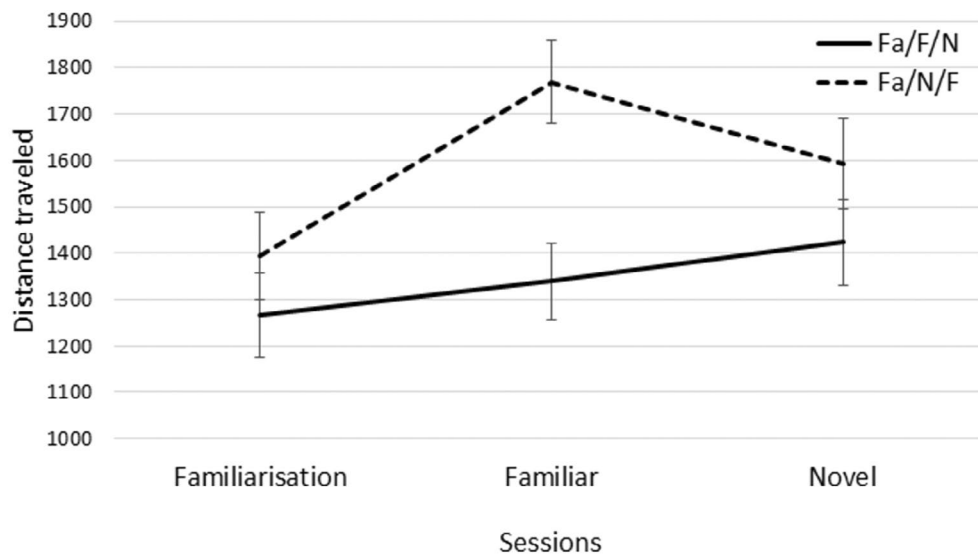


FIGURE 3 | Distance traveled as a function of the condition of exposure (familiarization, familiar, novel) and the order in which virtual environments are presented. Fa/F/N: order = familiarization, familiar, novel; Fa/N/F: order = familiarization, novel, familiar.

The Pearson correlation analysis did not indicate an association between the distance traveled during the exploration of the novel virtual environment and the novelty-related memory benefit score for word recall after deep encoding ($r=0.28$, $p=0.10$) and for words after shallow encoding ($r=-0.33$, $p=0.06$). Correlations were not significant either when considering the difference in distance traveled between the novel and the familiar environment (novel minus familiar), deep encoding, $r=-0.14$, $p=0.42$; shallow encoding, $r=0.25$, $p=0.15$.

3.1.4 | Questionnaires

The comparison of scores obtained in the IPQ questionnaires between the conditions where the N environment was explored and the condition where the F environment was explored did not indicate a difference, $t(34)=-1.18$, $p=0.24$, $d=0.13$. The correlation analysis did not show any significant relationship between the novelty-related memory benefit scores and the difference in presence between the novel and the familiar environment (deep: $r=-0.08$, $p=0.63$; shallow: $r=0.09$, $p=0.62$).

Regarding the personality questionnaires, there was no significant correlation between the scores reflecting novelty-seeking temperament and curiosity and the novelty-related memory benefit scores (deep: TCI-R, $r=0.11$, $p=0.54$; NEOPI, $r=0.11$, $p=0.54$; shallow: TCI-R, $r=-0.21$, $p=0.23$; NEOPI, $r=-0.15$, $p=0.38$). Personality scores did not show any correlation with distance traveled either in the familiar or in the novel environment (r 's <0.16 , p 's >0.36).

Finally, the comparison of the novelty-related memory benefit scores between participants with ($n=14$) or without ($n=20$) experience with VR and/or video games indicated no differences: deep encoding: $t(32)=0.73$, $p=0.46$, $d=0.26$; shallow encoding: $t(32)=-1.36$, $p=0.18$, $d=0.48$; across levels of processing conditions: $t(32)=-0.80$, $p=0.42$, $d=0.28$.

4 | Discussion

The current study assessed whether exposure to environmental novelty promotes episodic memory for words encoded immediately after exposure, especially when the memory trace for these words is weak because of shallow encoding. The level of processing manipulation was successful in creating better memory for words in the deep encoding condition than in the shallow encoding condition. Based on the model of Duzskiewicz et al. (2019) relative to the impact of novelty on episodic memory, we expected that exposure to novelty would improve memory performance for words in the shallow encoding condition, whereas it would not, or to a lesser extent, for words in the deep encoding condition.

The results partially support this hypothesis. Indeed, for words in the shallow encoding condition, there was a beneficial effect of exposure to novelty on free recall, but only when the novel environment was explored in the last session. When the novel environment was explored in the second session, novelty had no benefit on recall performance for weakly encoded words. For words in the deep encoding condition, there was no main effect of novelty. However, novelty and session order interacted: free recall was higher in the novel than familiar condition when the novelty condition occurred first and participants performed the episodic memory task for the first time, but not second (F/N). The pattern was reversed for the familiar first (F/N) condition, with higher recall in the familiar rather than novel condition, again when the memory task was performed for the first time.

There was no effect of novelty for recollection- and familiarity-based recognition memory of words that participants did not recall. As recalled words were likely to be recollected because of a retrieval practice effect or testing effect (Roediger 3rd and Butler 2011), the differences in the results for recollection scores for all items versus nonrecalled items may reflect this effect more than an influence of variables on recollection. In contrast,

nonrecalled words may have been less well recognized because of an effect of retrieval-induced forgetting (i.e., the fact that the memory traces of recalled items are reinforced at the expense of nonrecalled items (Anderson et al. 1994)). Retrieval-induced forgetting creates a condition of weaker memory traces during the recognition memory task. Contrary to the prediction that novelty exposure would benefit weaker memory traces, there was no effect of the novelty of the environment on the recognition performance for nonrecalled items.

The pattern of findings for the recall task adds to the complexity of the picture regarding novelty and episodic memory. Given that previous work in animals has shown that exposure to novelty is particularly beneficial to weak memory traces (Wang et al. 2010), we assessed the potential benefit of exposure to novelty on verbal memory as a function of the level of processing. Consistent with the prediction, free recall of shallowly encoded words was better after exploration of the novel environment than after exploration of the familiar environment. However, this was only when the novel environment was explored in the last session. The last session was also associated with more exploration behavior, but we did not find any correlation between the distance traveled and novelty-related memory benefit. The lack of a novelty effect for weakly encoded words when the novel environment was explored first may be a consequence of the session effect of the other words of the list (deep encoding), as data relative to deeply encoded words point to a pattern mainly dependent on the order of sessions. Indeed, in the deep encoding condition, there was a systematically higher performance in Session 2, when performing the memory task for the first time, than in Session 3 (i.e., the last session), suggesting the presence of some other memory-promoting factor in the design.

When one performs an episodic memory task repeatedly, stable performance or a practice effect is observed (i.e., improved performance at retest) (Benedict and Zgaljardic 1998). Here, we observed no practice effect, as free recall was poorer the second time participants performed the word memory task. Moreover, the level of processing effect was attenuated in the last session compared to the second session, as evidenced by a decrease in the recall of deeply encoded words and a slight increase in the recall of shallowly encoded words. Several nonmutually exclusive explanations may account for this observation. First, because the procedure was similar in Sessions 2 and 3, there may be proactive interference whereby encoding of the new list of words is impoverished because attentional resources decrease from the encoding of the preceding list to the current encoding of the new list, due to competition from previously encoded words (Crowder 2014; Wixted and Rohrer 1993). Deep encoding would suffer more from this decrease in attentional resources because it is the most demanding condition, as observed here. Second, participants may have been less motivated and dedicated to the task when coming to the lab for the third time and engaged less in the memory task, as shown previously (Schomaker and Wittmann 2021). Such lack of motivation did not appear in the measure of the distance traveled in the virtual environment, as participants walked a longer distance in Session 3 than in Sessions 2 and 1. This would rather indicate more motivation to explore in the last session than the first or more efficient exploration in the later session due to practice effects. But the attenuation of the level of processing effect in the last session

may reflect less effort in elaborate encoding for the memory task itself. Third, the arousing and positive emotional effect of experiencing VR (Pavic et al. 2022) may be higher in Session 2 than in Session 3. This would, particularly, benefit deeply encoded words because arousal and emotion contribute to elaborate encoding (Buchanan et al. 2006). Consistently, a recent study suggested that the mere fact of experiencing VR for the first time has a memory boosting effect (Servais and Bastin 2025).

As for words encoded with shallow processing, they were not sensitive to the memory boosting effects operating during Session 2. As memory for deeply encoded words was boosted and because both deeply and shallowly encoded words had to be recalled in the same trial, words from the deep encoding condition may have overwhelmingly come to mind and interfered with words from the shallow encoding condition (thus creating output interference). It is only during the last session that the beneficial effect of environmental novelty on recall of weak memory traces could operate, but this occurred because participants engaged less in elaborative encoding for deeply encoded words, which were less well recalled, and thereby reduced output interference with the shallowly encoded words. Finally, one cannot exclude that participant differences partly drove the session order effect, as distinct groups performed the two orders. However, there was no main effect of the order on global recall performance, and general differences in memory performance between the groups cannot explain the differential effects for novelty observed in the current study (e.g., familiar > novel for F/N and novel > familiar for N/F).

The use of a within-subject design put forward the fact that the order of presentation of the environment and the history of exposure could play a role. In addition to the interference effects mentioned previously, it may also be that how much participants are exposed to a familiar environment modifies the impact of exposure to a novel one. Here, novelty was associated with improved memory for shallowly encoded words after 2 exposures to the familiar environment (i.e., last session), but not after only one exposure to the familiar environment (i.e., second session). Potentially, participants failed to explore the entire environment in one exposure round, leaving certain aspects to be novel to them when they are exposed to it a second time, which would limit the difference between the novel and familiar environments in our design. To test the hypothesis that more extensive familiarization with an environment is necessary for a novelty effect to occur, a future study may test memory for words after participants explored either a novel or a familiar environment (in a between-subjects design) after two exposures or potentially longer exposure to the familiar environment, allowing for exhaustive exploration of this environment. In the current experiment, when assessing the effect of the novelty of the environment in a between-subjects design after only one exposure to the familiar environment, there was no significant effect of novelty.

Although the current design was very similar to that used by Schomaker et al. (2014), there was no clear evidence that the novel environment triggered more interest and motivation than the familiar environment. Indeed, the feeling of presence did not differ between the two conditions, contrary to what was observed in Schomaker et al. (2014). Even though there are

conflicting findings, it has been suggested that the sense of being there may promote memory encoding by favoring selective attention (Makowski et al. 2017). In line with Schomaker et al. (2022), the novel environment was not explored more—as measured by distance traveled—than the familiar environment. However, in the current study, more exploration was observed in the novel compared to familiar conditions in Session 2. Therefore, it could be that the environmental novelty of the environment we used was not sufficient to affect subsequent memory performance. First, the virtual environments were perhaps not stimulating enough in our study. They were relatively simple and contained few objects, which may have induced limited curiosity and surprise. They contrast with the detailed environments used by Schomaker et al. (2014). Second, currently, young participants, in general, may be more familiar with the graphism of Unity environments, as this software is commonly used to create video games. As such, exploring a noninteractive environment in VR may have been a novel experience for most individuals a few years ago, but this may no longer be the case in 2022. Of note, however, we found no effect of the habit of playing video games and/or having already experienced VR on the participants' memory performance. Finally, it may be that the familiarization session was not sufficiently long to allow participants to get as familiar as they can be with the initial environment. In addition to assessing longer familiarization sessions, as mentioned above, future work should also include a measure of the sense of familiarity gained by participants, or should include more specific measures related to exploration of the environment (such as area covered or number of landmarks discovered).

The main limitation of the current study is the lack of characterization of the environments beyond the sense of presence and distance traveled. As VR and novelty can influence memory via different mechanisms, it would have been of interest to add ratings of motivation, emotion, arousal and attention. Moreover, one cannot exclude that participants familiarize more quickly with one environment (Island) than the other (Alien), as indirectly suggested by the difference in distance traveled. It therefore is possible that the Alien environment remained more novel to participants. Nonetheless, this did not seem to affect the novelty-related results.

Regarding individual differences, we did not find any association between the personality traits of curiosity and novelty seeking on the one hand and the effect of novelty on episodic memory on the other hand. These results are consistent with those of Schomaker and Wittmann (2021), who also administered the TCI-R to participants and reported no significant association between novelty seeking and memory scores. The personality traits of novelty seeking and curiosity thus did not modulate novelty-related memory performance in the current study.

Finally, the current study used VR as a tool to manipulate environmental novelty and its effect on memory in a subsequent memory task. VR has some properties (e.g., visual fidelity, multimodal sensory information, active exploration) that in themselves may enhance memory, notably for information encountered during the exploration (Smith 2019). The use of VR in this experiment may have contributed to some observed effects, such as the memory boost in Session 2 for deeply encoded words. Recently, it was observed that experiencing VR for 15 min

improved memory in a subsequent verbal recall task compared to watching a documentary for the same duration (Servais and Bastin 2025). So, future studies should unpack the properties of VR that have a positive and persistent influence on memory processes.

In conclusion, the observed pattern of findings does not align with any previous results (Biel and Bunzeck 2019; Fenker et al. 2008; Quent and Henson 2022; Schomaker et al. 2014; Schomaker and Wittmann 2021). On the one hand, there was a session effect whereby free recall of deeply encoded words was better during the first administration of the task than during the second administration. On the other hand, memory for words that were shallowly encoded benefited from exploring the novel environment in the last session only. This encourages future studies to consider the optimal conditions under which one can observe the beneficial effects of each type of novelty on episodic memory (Lorents et al. 2023).

Author Contributions

Camille Aron: data curation, investigation, formal analysis, visualization, writing – original draft. **Judith Schomaker:** conceptualization, methodology, software, validation, writing – review and editing. **Christine Bastin:** conceptualization, data curation, formal analysis, funding acquisition, methodology, project administration, resources, visualization, validation, supervision, writing – review and editing.

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Ethics Statement

This study was performed in line with the principles of the Declaration of Helsinki. The study was approved by the ethics committee of the Faculty of Psychology of the University of Liège (No. 1920–110).

Consent

All participants signed a written informed consent before participating in the experiments.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are openly available in OSF at <https://osf.io/f3aps>, reference number f3aps.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** Supporting Information.