Enhancement of spatial memories at the associative and relational levels after a full night of sleep and likelihood of dream incorporation

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Summary. This study evaluated the effect of sleep in mediating the performance of associative and relational spatial memories in an immersive spatialised task. It also investigated how items presented during the task were incorporated into participants' dreams. A total of 54 participants were assigned to either a wake or sleep condition in their home setting: 27 participants stayed awake during a normal day between the learning and the testing phases of a spatial task, while 27 other participants slept in their home according to their usual sleep schedule. Subjective dream experiences during the night were reported by the participants using a paper/pencil diary. Results showed that memory performances for the testing phase were greater for the Sleep group at both associative and relational levels compared to an equivalent period of wake. The examination of dream reports revealed that 6 dream reports out of 17 (35.29%) collected in the Sleep group incorporated items related to the task. To our knowledge, this study is the first to demonstrate a protective effect of sleep on associative and relational memory performance using an immersive spatialised VR task and with a full night's sleep occurring in a home setting that respected the participant's usual sleep schedule. As a perspective, we proposed methodological improvements for future studies investigating dreams and their relationship with memory processes.

Keywords: Memory, sleep, dreams, virtual reality, associative memory

1. Introduction

Our daily life is composed of episodes that are integrated into a dense and dynamic memory network that intertwines the traces of current episodes with those of our past history (Nadel, Hupbach, Gomez, & Newman-Smith, 2012; Versace et al., 2014). What we encounter is always taking place in a three-dimensional spatialised world and a spatial property of an episode are posited to be fundamental to memory (Cerles, Guinet, & Rousset, 2015)

1.1. Associative processes in memory

The idea that episodic memory is based on associative processes is not new and can be traced back to the emergence of experimental psychology (James, 1890). Consideration for such associative processes has led to several theorization that illustrated their importance in explaining memory performance (Anderson & Bower, 1973). More recently, Nadel, Hupbach, Gomez and Newman-Smith (2012) have proposed that consolidation is not a phenomenon occurring in isolation but is part of a dynamic process leading to systemic changes in the brain's network. In other words, the experience must be integrated into the memory system in order to be stored and to allow later recall. This integration is the consequence of the system changing from its previous state when it comes into contact with the world (Nadel, Samsonovich, Ryan, & Moscovitch, 2000). Thus, memory is about creating links between newer and older experiences through mechanisms that reshape previously fixed memories and these transformations are triggered according to the similarities between previous and current experiences. In simple terms, this dynamic process essentially consists of associating and relating similar experiences. Associative memory can be thus considered as referring to the tendency of the memory system to link together events that occur in the lives of individuals.

The appraisal of the associative process is divided into two main levels in this study, one is termed associative and refers to links that are created between items perceived in the same time frame, the other is termed relational and refers to links that are created between items that share similarities even though they were not perceived in the same time frame. The relation that is formed between such items is also usually referred as relational memory (Ellenbogen, Hu, Payne, Titone, & Walker, 2007). These two levels of memory have been evaluated using a research paradigm called associative (or transitive) inference (Preston, Shrager, Dudukovic, & Gabrieli, 2004). The inference refers to the relation that can be inferred from two associations that share a common feature. In other words, with such a paradigm, if A is in association with B and B is in association with C, then a relation between A and C can be inferred. Within this scope, the AB and BC links concern associative memory while the AC link concerns relational memory. A classic example would be one of the family relationship (if A is the mother of B, and B is the sister of C, then A is the mother of C).

At the physiological level, Zeithamova, Dominick and Preston (2012) have shown that association and relation mechanisms are likely to depend on how activation of the

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hippocampus and the Ventromedial Prefrontal Cortex are correlated when learning associations. In addition, Preston and Eichenbaum (2013) indicated that the episodic properties of an event (e.g., its spatial and temporal organization) are reflected in the response patterns of individual hippocampal neurons during the episode but are also reactivated during the offline treatment period. These processes take the form of a reactivation occurring, for example, during sleep, which allows the transfer from the hippocampal activation center to the prefrontal activation center, which coincides with the (semantic) integration of traces of recent events with those of past experiences (Genzel, 2020). In the scope of the Complementary Learning Systems framework (McClelland et al., 1995), this integration is assumed to take the form of a gist extraction based on overlapping properties of events such as those formed in the associative inference task for relational levels (Lewis and Durrant, 2011).

1.2. Sleep, Dream and Memory Performance

The benefits of sleep for memory are well established and demonstrated as operating at a rather large scale (Diekelmann & Born, 2010; Walker & Stickgold, 2006). The extent of sleep's contribution to associative memory has also been subject to research, for instance, in a systematic review, Chatburn, Lushington, and Kohler (2014) illustrated in a healthy adult population, the facilitative effect of sleep on associative performance. . Cherdieu et al. (2018) proposed a theoretical framework to understand how sleep promotes the emergence of new relations based on the components that are incorporated into the memory system.

Recently, two studies showed that both associative and relational performances were enhanced for individuals who slept during a whole night compared to individuals who stayed awake for a typical day. The first study (Huguet, Payne, Kim, & Alger, 2019) was conducted within a laboratory setting using polysomnography and the other (Ribeiro, Gounden, & Quaglino, 2020) occurred in the participant's home in a typical sleep context. In this last study, the authors demonstrated that in the case where the content of written dream report was similar to an item seen during the learning phase, associations involving these items were likely to be better recalled during the post-sleep recall phase. To be more precise, in the mentioned study, the associations were composed of an image of a face associated with an image of an object (for example, knife, chair, sheep, paperclip). In the dream diary, completed by 31 participants in the Sleep group, 18 participants (58.06%) reported one or more dreams about the study of which 14 items were identified. Of the 28 associations that involved these 14 items, 26 were correctly recalled (92.86%). In addition, at the time of recall, they could indicate whether they thought they had dreamed about the association they were recalling; when they did, they performed better for that association. This study (Ribeiro, Gounden, & Quaglino, 2020) is in line with previous studies demonstrating that dream content can incorporate items from an experimental situation (e.g. a maze orientation task) and that this incorporation is linked with better memory performance (Wamsley & Stickgold, 2019; Wamsley, Tucker, Payne, Benavides, & Stickgold, 2010). The difference in memory performance following a delay consisting of either sleep or wake after learning is considered as the demonstration that a reactivation of memory traces during sleep is likely to lead to its consolidation (Payne, 2011).

1.3. Spatiality, Sleep and Memory

It is well established that sleep promotes the integration of spatial information in long-term memory (Orban et al., 2006; Rauchs et al., 2008). The use of virtual reality (VR) technology for such investigation seems to be a good strategy to study spatial memory as it provides a complex environment or scene and it allows the participant to move freely in a 3D space. The use of this technology is interesting because, firstly, the two-dimensional screen classically used can be considered as far remotes from what an individual encounters in his daily life and, secondly, scenes facilitate associative memory and relational integration (Robin & Olsen, 2019). In two experiments, Robin and Olsen (2019) found that memory performance was better for associations that included scenes (a spatial context) compared to objects and faces. However, to our knowledge, how sleep enhances associative memory of spatialise d items has only been demonstrated once within an immersive 3D space (Ribeiro, Sagnier, Quaglino, Gounden, & Loup-Escande, 2020).

In this aforementioned study, it was demonstrated that a period of rest enhanced associative memory performances with no significant effect on relational ones (Ribeiro, Sagnier, et al., 2020). However, the authors proposed a 20 minutes nap window with or without sleep and no significant benefit of sleep on relational memory was observed in line with Ellenbogen and collaborators (2007) indicating that relation in memory requires both time and sleep . With an emphasis on such offline period and considering the limits of this previous study (Ribeiro et al., 2020), the present research aims at further expanding these investigations concerning the changes of spatial memory at the associative and relational levels by proposing a complete night sleep occurring in the participant's home setting.

1.4. Aims and Hypotheses

The main aim of this study is to evaluate how a full night sleep contributes to spatial memory performance for items displayed in a VR environment. We postulated that performance would be better at both the associative and relational levels after a sleep period than after a wake period. As a secondary aim, we sought to evaluate the likelihood of items from the task to be incorporated in dreams. We expect that associations implicating items incorporated will be more likely to be recalled than the others.

2. Method

2.1. Participants

Fifty-seven undergraduate college students from Picardie Jules Verne University (44 women, 13 men; M = 21.42 years, age range: 19-26 years) were enrolled on a voluntary basis in this study. Prior to entering the protocol, all participants signed a consent form indicating the main goal of the study, the time required to complete the study, the possibility of requesting the deletion of their data, and the anonymization of all data used in communication. The exclusion criteria were having a diagnosed sleep disorder ongoing during the last two years and having a photosensitive epilepsy. Participants were informed that they should stop the experiment if they experienced symptoms of cybersickness. No participant reported cybersickness during the protocol. Participants were randomly allotted in the two experimental group (Sleep and

Wake). Participants were included from February to March 2020; these inclusions were discontinued due to the COVID situation and the start of the confinement.

2.2. Material and Measures

The headset used in this study was an HTC Vive displaying 1080x1200 pixel for each eye. This headset yields a 100° horizontal field of view with a refresh rate of 90 Hz. It was connected to an HP ZBook 17 G3 with an Intel Core i7 (Quad-Core 2.6 GHz / 3.5 GHz Turbo), 8 GB RAM and a NVIDIA Quadro M5000M graphic card. The environment was developed using the Unreal Engine 4.

The items were composed of 3D models depicting 24 objects: Green plants, Computer, Spray can, Sledge, Car, Cactus, Gift box, Rock, Camera, Stool, Ball, Mushroom, Hat, Toilet, Pumpkin, Fire extinguishers, Violin, Dice, Bread, Hammer, Crow, Fish, Saw, Armchair. The graphic appearance of the items was preferably chosen for the realistic and compatibility with an accurate representation of the it. However, as the models came from different authors, the graphic identity was not identical between the items. A figure presenting the items is available on request to the corresponding author of the present article (the items are not presented in order to ensure the novelty of the items in the context of future studies).

Concerning the order of the different steps (see Figure 1), it can be summarized as such: there was a first learning step presenting half of the item-location associations (A-B), immediately followed by a first immediate associative cued recall for these associations (A-B). The second half of the item-location associations were proposed (B-C) also followed by an immediate associative cued recall for these associations (B-C). After a 12-hours delay, participants performed the delayed relational recall (AC) immediately followed by the delayed associative cued recall (A-B, B-C).

The environment, labelled Associative and Spatialised Memory Room (ASMR), was identical to the one used in the study of Ribeiro, Sagnier, et al. (2020) in which 12 display stands (B) were disposed in front of the participant, 4 on the left side, 4 on the back side and 4 on the right side. Each display stand was covered to only show the item (A or C) when the participants pressed a button placed on the stand (B). For each revelation, a luminous mark on the button indicated which display stand (B) was to be opened. By pressing the button with a standard controller, the participant would hear a clicking sound. The whole room was illuminated using an omnidirectional light source placed in the middle of the display stands (B). The size of the environment was about 16 square meters (4x4 meters). All movements in the environment were similar to real life, as participants had to walk (i.e., it was not possible to teleport). A black cross was drawn on the floor to indicate to the participant where he or she needed to go after a given item (A or C) was revealed for 5 seconds. During the associative recall s (A-B, B-C), a supplementary display stand was shown in the center of the room to display the item (A or C) for which the participant had to indicate the location (B). A laser pointer was available and movable by the participant to indicate which stand (B) they thought they had previously seen the item (A or C) displayed. During the relational recall (A-C), a table showed an item (A or C) seen during the learning phase and the participant had to indicate aloud with which item (A or C) it was related.

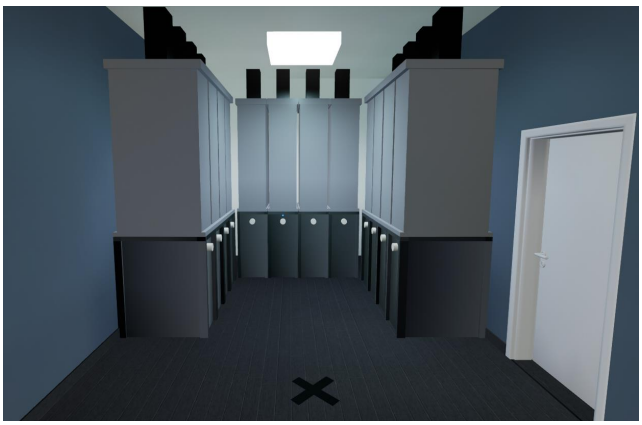

Figure 1: Screen capture of the Associative Spatialized Memory Room (ASMR)

Concerning the scoring computation, the association of each item (A or C) to a display stand in the room (B) gives one point (for the associative score), and the identification of an item (A or C) that appeared in the display stand as another one but at different times gives one point (for the relational score (A-C)). In other words, each correct recall granted the participant 1 point. Scores for immediate associative recall (A-B, B-C) and delayed associative recall (A-B, B-C) were integers (min = 0/24, max = 24/24). Score for relational recall (A-C) was integer (min = 0/12, max = 12/12).
A questionnaire was proposed at wake for the Sleep group and just before the delayed recall for the Wake group. For the Sleep group only, a question was additionally proposed to assess dreams of the previous night using the following wordings “Describe your dreams (story, impressions, thoughts and emotions from that night) as exhaustively as possible”. This questionnaire also evaluated sleep duration from the previous night and mentation on the experiment in both groups using the wordings:” Have you thought about the experience since the learning session?”. This question was designed only as a measure aimed at neutralizing the spurious potential effect of making one group possibly having the study items recalled (in dreams report) but not the other and was, thus, not analysed.

As an exploratory measure outside the scope of this study, seven participants in the Sleep group wore a Dreem headband, which is designed as a comfortable and lightweight device (130 gr) consisting of dry EEG electrodes designed to assess sleep architecture. Its use in this study was for exploratory purposes only to assess its potential applicability in studies such as this one.

2.3. Procedure

Participants were placed in the virtual environment (ASMR). During the learning task, each participant was instructed to stand on the black cross and identify the display stand (B) with the luminous marker. They were then requested to go toward the display stand (B) and open it by placing the hand on the button and wait for the display stand to close (after 5 seconds) while looking at the item (A). Participants then had to go back to the cross and state aloud which item (A) he or she had just seen while looking at the back wall. The participant had to repeat the procedure for the next item until all 12 items (A) in the room were seen once. The participant then performed a first associative recall (A-B) by indicating with a laser which display stand (B) contained an item (A)

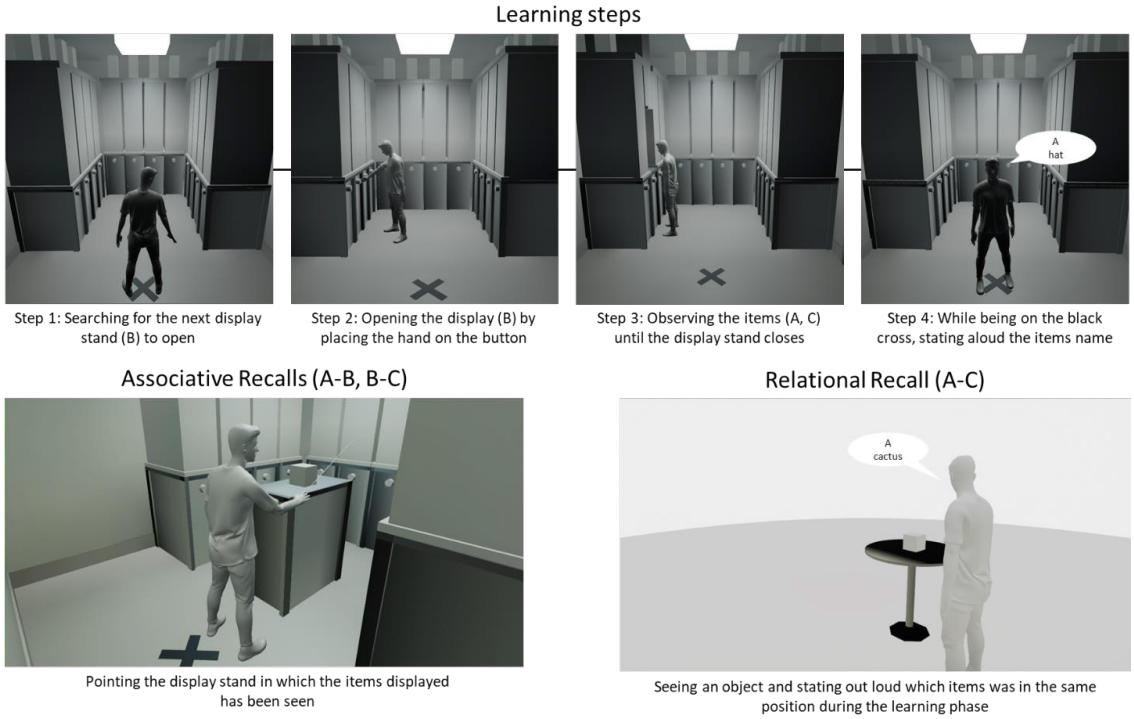

Figure 2: The learning phase steps was done twice: Phase 1 with 12 items and Phase 2 with 12 new items). During the associative recalls the participant saw an item (depicted here using a cube) on a display stand in the middle of the room and had to grab a laser pointer to indicate where he/she thought to have seen the item. During the relational recall, the participant saw an item on a table inside a neutral environment and had to indicate out-loud which other item was in the same position during the learning phase. All items order and place were fully randomized by the software. The individual in these pictures only serves as a representation of the participant and was not present in the environment during the learning process.

displayed on a central display stand. The room was reloaded with 12 new items (C) and the participants performed the second learning task (B-C) and immediate associative recall task (B-C). After a 12h delay at home containing either sleep or wake depending on the group, participants came back to the laboratory and had to perform the relational recall (A-C) in which they had to indicate aloud which item (A or C) had the same position (B) in the ASMR as an item (A or C) displayed in front of them. During this relational recall (A-C), participants were placed in a circular empty environment to ensure that spatial cues from the ASMR were not used to infer the relationships. Finally, they performed the final associative recall (A-B, B-C) in the ASMR using the laser in the same fashion as the immediate associative recall (A-B, B-C). This procedure is summed up in the Figures 2 and 3.

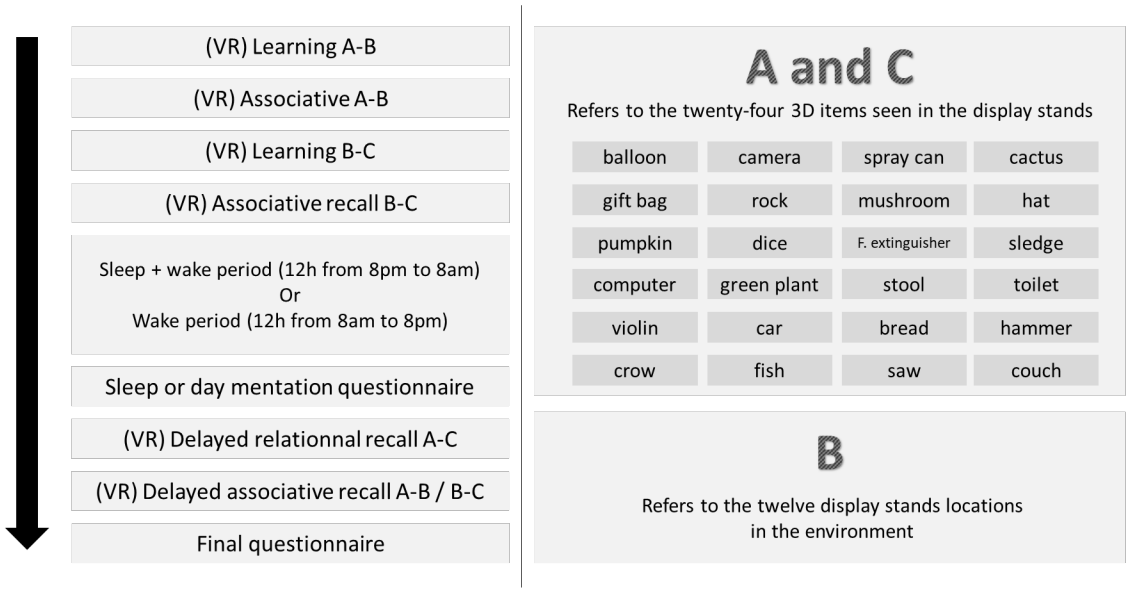

Figure 3: Protocol sequence for all participants (left) and corresponding items (right).

2.4. Statistical and report analysis

All statistics were performed using Excel for reporting recall scores, Jamovi for performing statistical tests and R for calculating recall scores and performing a simulation in which we searched for occurrences of our items in past studies dream narratives. This simulation was conducted to determine the spontaneous occurrence of our items in dream narratives.

Three participants of the Wake group were excluded from the final analysis as they did not at least recognized half of the associations at the immediate testing. All statistical significance outcomes (in the result section) set at $p < .05$, were identical with or without this exclusion while it negatively impacted effect size.

Seven participants in the Sleep group wore a Dreem headband during the night . They were included in the final analysis but, in order to control for an eventual spurious effect, the statistical tests presented in the result section were again performed while excluding those 7 participants . All statistical outcomes were also identical in terms of significance (set at $p < .05$).

For the analysis of the dream reports and the identification of incorporation, we collected all the names of the items mentioned aloud by the participants during the learning phase for which we searched for a direct correspondence in the dream reports using the search function of our text editor. For example, the term computer and PC were searched for in each report because different participants referred to that item with either word during the learning phase. This method was preferred over inter-rater scoring, to facilitate a better comparison with a previous large dream samples available online that give access to the whole report set through such word matching (see the result section). Where matching with English was necessary (as mentioned in the results section), the first translation proposed by the Deepl translation software was used. The word used for each item can be found in the left column of Figure 6.

On the basis of the theory of frequentist statistics, in order to determine whether the incorporation was consecutive to the experimental situation or to the normal expression of the phenomenology of the content of the dream, it is necessary to define the likelihood that this observation occurred spontaneously. First, we used a sample of 932-night reports containing one or more dreams from a previous study (Ribeiro, Gounden, & Quaglino, 2018) that was similar to the present one in terms of age, gender, occupation, location, and time of collection (February to March) and thus also involved French students from the Jules Verne University (69 women, 12 men; M = 21.63, age range: 18-25). Secondly, we also used a sample of 5904 dream reports exported from website sleepanddreamdatabase.org under the label "Online dreams 2015" (44 female, 36 males, age not disclosed). Both samples were not related to the present study's items. We estimated the likelihood to observe 6 or more items from our present material when picking up randomly 11 dream reports among those two samples. See Figure 6 for a graphical representation of this likelihood based on a simulation of 106 random picks. The R script is available in the supplementary section.

Table 1. Scores for Wake and Sleep groups at immediate associative, delayed associative, and relational testing

	Wake group (n = 27)	Sleep group (n = 27)
Immediate associative	18.4 (3.23)	18.9 (2.63)
Delayed associative	13.1 (4.38)	15.9 (4.57)
Relational	2.22 (2.13)	3.59 (2.19)

Note. All scores are reported as such: Mean (Standard Deviation)

3. Results

3.1. Memory performances

The scores are presented in Table 1. For associative performance, a repeated-measure ANOVA was performed on the two associative recall scores as dependent variables. The condition (sleep or wake) was used as a between subjects' factor and the moment (immediate/delayed) was used as a within subjects' factor. There was a significant effect of the moment (F (1, 52) = 73.92, $p < .001$, $\eta^2_p = .59$), and a significant interaction effect (F (2, 80) = 5.66, $p = .021$, $\eta^2_p = .01$) showing that the decrease from immediate to

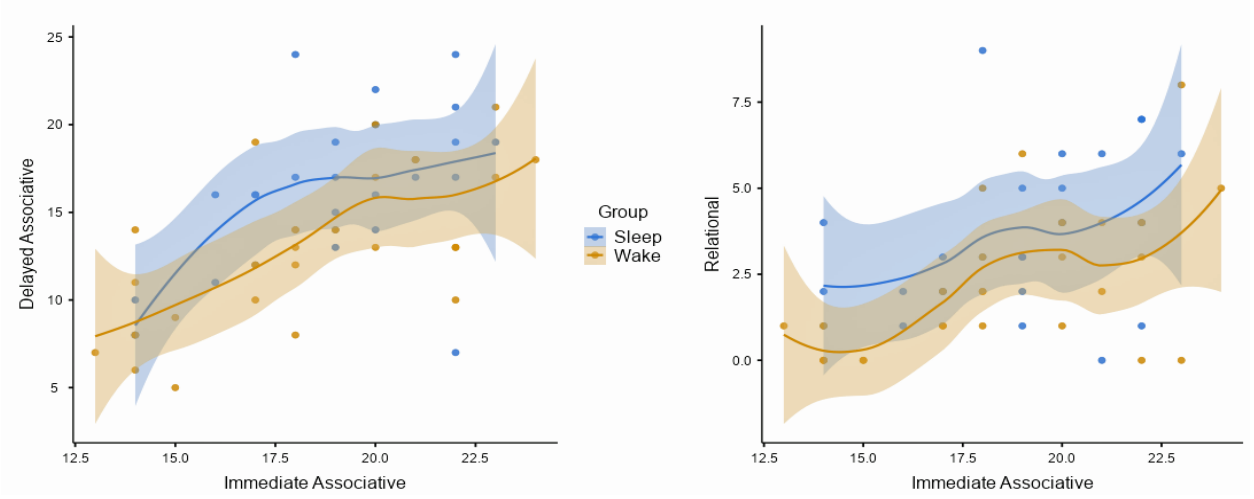

Figure 4: Data distribution across the Sleep group (blue) and the Wake group (green) for associative recalls (left) and relational recall depending on immediate performance (right).

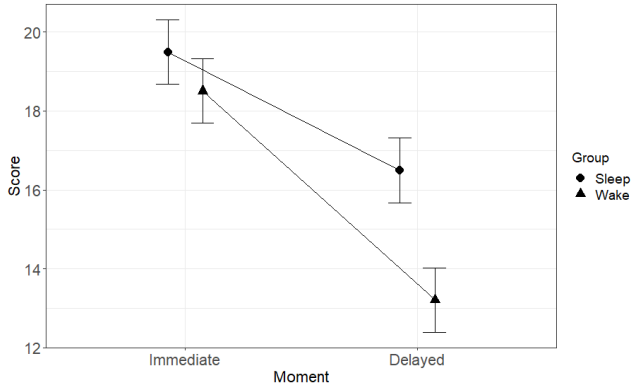

Figure 5: Associative recall score at immediate and delayed moments showing that the decrease in performance after the delay was less important for the sleep group than for the wake group (p = 0.021).

delayed associative recall was less important in the Sleep group than in the Wake group. Figure 4 (left) shows how the score concerning immediate and delayed associative recalls were distributed across the two groups (sleep: *n* = 27; wake: *n* = 27). Figure 5 shows the interaction between group and testing moment for associative recall scores.

For relational performance, Relational performance was also compared for the two-group using an independent sample T-test showing that the scores were different (*p* = .021, cohen's *d* = .65). To control for difference that could have been caused by immediate encoding, an ANCOVA was performed on the relational score. The condition (sleep or wake) was used as a between subjects' factor and the immediate associative recall scores served as a covariate. There was a significant group effect on relational performance (F (1, 51) = 5.41, p = .024, η^2_p = .09). Figure 4 (right) shows how the relational scores were distributed across the two groups depending on the immediate associative recall score (*n sleep* = 27; *n wake* = 27).

3.2. Dream Incorporation

In the Sleep group, the dream content was assessed using written reports. We were able to identify which report contained mentions of items seen during the learning phase by employing a word matching strategy using the item's name. Precisely, 11 participants from the Sleep group (out of 27, 40.74%) reported 17 dreams at awakening (Mean word-count: 69.94) and among them 6 incorporated a studied item (6 participants out of 11, 54.54%; 6 dream reports out of 17, 35.29%). The incorporated items were cars, pumpkin, toilets, computers, gift and hammer. The translated dream reports are available in Table 2 and all dream translation are available as supplementary material.

Based on the first comparison sample that was similar to the present one in terms of age, gender and occupation, there was a 1 in 564 chance (0.18%) of observing data corresponding to the data we currently have. Based on the sample of the "Online dreams 2015" available on the sleepanddreamdatabase.org, there was a 1 in 24 chance (4.23%) of observing incorporation as in the present study. It is therefore unlikely that our data would express typical dream content. In other words, these results support our hypothesis that the dream reports obtained in the present studies are indicative of the incorporation of items in dream content. See Figure 6 for a graphical representation of this likelihood test.

Items	Ours (2018) N = 932	Online study 2015 N = 5904
spray paint can	0	0
Dice	0	0
Extinguisher	0	0
Saw	0	0
Hammer	1	1
cactus	0	2
Stool	0	2
Mushrooms	0	3
Violin	0	3
Luge	0	6
Pumpkin	0	7
Plant	0	10
Bread	1	19
Pebbles, rock	1	20
Hat	0	26
Gifts	3	31
Crow, bird	0	32
Camera	4	34
Toilet	13	38
Balloon	2	48
Fish	3	54
Couch	3	67
Computer, pc	1	76
Car	47	467

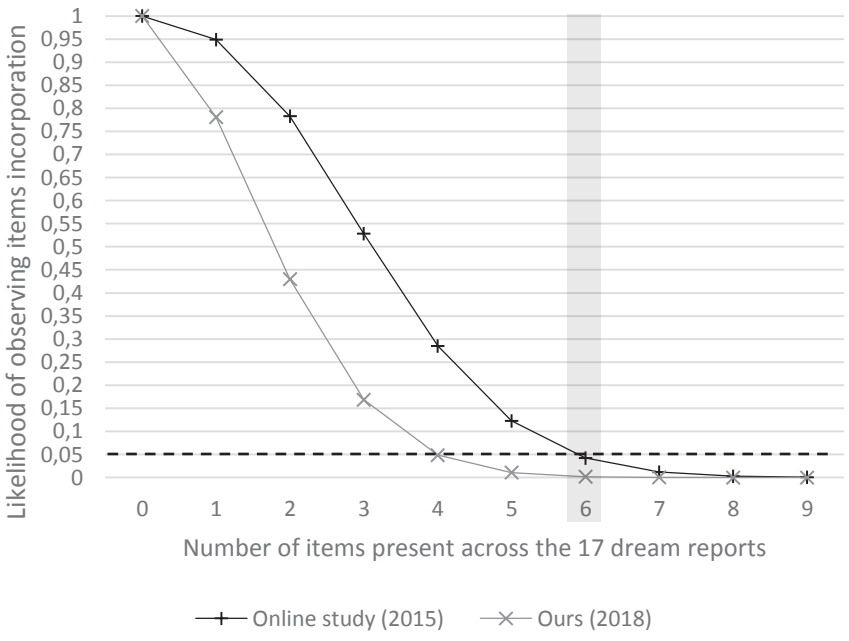

Figure 6: Items occurrence in unrelated dream sample (left) and the extracted probability of observing items from this study when picking an equivalent sample size (N = 17) from unrelated dream reports samples (right). The dashed line represents the p-value threshold set at 0.05. The light grey line represents a data set from a previous study with similar participants but an unrelated task (Ribeiro et al., 2018). The black line represents the "online dream 2015" data set from the Sleep and Dreams database. As a reminder, 6 items were incorporated to the present study dream reports.

Table 2. Transcription of the dream report (translated from French into English) presenting an item's incorporation, the matching words are underlined.

Participant ID	Dream report	Word count
3	Quite blurry, I think that with my friend we found a dog that belonged to one of his acquaintances. We got into his **car** to what looked like a grouping, a **car** meeting. My parents joined us, argued and I wanted to go back by taking their **car** (which was by no means the one they actually have). I changed my mind and, walking home, I passed my 15-year-old brother at the wheel of a **car** and all I remember is a gunshot.	90
4	I dreamed about the objects I had to enunciate during the study the day before and I remember the **pumpkin** in particular, It was a nightmare about what is important to me in my life, and the fear of losing it and my boyfriend was leaving me.	44
6	it was a survival among infected beings, not zombies because they were talking but beings who wanted to kill us to infect us. It was worse than zombies because they were talking and running like us...so my dream was to run away, hide and be afraid (I often have dreams like this) I remember at the end of my dream I saw a small room with toddlers in a **toilet** in what seemed like a very small school and if at some point the infected arrived, the room would get blocked and food would come out of the wall by a mechanism to let the children survive...for a while. At the same time as the room was being shut down, you could hear "you die", instead of dying infected, they would actually starve to death... we were locked with a group of students in an amphi-theater waiting for the bad guys outside to let us go and not kill us...(they were armed).	171
7	I was on my way to college with a friend but on the way I realized that I forgot my **computer**. I wanted to turn around and get it back, but two girls from the college blamed and insulted me. In the end, I couldn't get my **computer** back in time.	51
8	It was Christmas at my grandparents' house. I was getting a great **gift** and my brother a lousy **gift**. But then we would open our common **gift** in the dining room. It was a tower to throw the baybled spinning tops (I don't know how to spell it) with a Pokémon (the big light pink chubby guy) figure on top to decorate.	56
9	I'm chasing a **hammer** in a night that seems eternal. I remember the moment I caught it I woke up. That's about it.	29

3.3. Dream content and memory performance

Concerning dream reports, among the 6 items incorporated, 5 (83.33%) were correctly recognized during the delayed associative recall. Interestingly, it should be noted that the item that was not correctly recognized (computer) was involved in a narrative implicating a loss *"In the end, I couldn't retrieve my computer in time"*. This sample of six incorporation was too small to statistically address this second part of the secondary hypothesis. Assuming that this sample was representative of what would have been obtained with a larger number of participants, 81 participants (providing 51 reports with 18 showing item incorporation) would have been required in the sleep group to achieve statistical significance (set at $p < .05$) in this study. This limitation will be discussed below.

4. Discussion

This study demonstrates that sleep enhances memory at both associative and relational levels. In terms of dream report, 11 out of 27 participants (40.74%) reported 17 dreams during the night and 6 (35.29%) were related to the items seen during the learning phase. Among them, 5 out of 6 dreams were correctly recalled during the associative recall phase, but it was statistically impossible to determine if these 5 items were better recalled than the others.

Concerning memory performance, the effect size, particularly for relational recall, was rather small. This could be explained by at least four factors or interpretations that could help guide the design of future studies. The first is that the spatial relations we have artificially created between the items may not be sufficiently distinct to compete other possible relationships; as an example the items used in our study could be linked according to common semantic characteristics that they shared, for instance, a stool and a sofa serve the same function, a saw and a hammer are both tools, a fish and a crow are both animals, and a green plant and a cactus may have been spatially perceived together many times during the participant's life. The second is that the spatial property may not be sufficient to generate a strong relationship between items. As a reminder, the spatial property of the experiment was central to this study because it is likely to be reactivated during the night and, to some extent, is at the heart of episodic functioning (Cerles et al., 2015; Hasselmo, 2009). However, being free to move around in an environment of about 15 square meters may not be sufficient to fully elicit this functioning. Beyond the sole size of the room, items may have been too close together and the display stands may have been too identical in the current version of the ASMR. The third is that in this study, as in previous studies using the associative inference paradigm (e.g. Alger and Payne, 2016) we did not inform the participant that he or she wouldbe asked to recall related items. Therefore, the encoding was intentional for the associative memory and incidental for the relational memory. It is interesting to note that a period of sleep is likely to promote intentionally encoded memory traces rather than incidentally encoded memory traces (Drosopoulos et al., 2005). Additionally, participants are likely to exhibit greater performance if they are told that there will be a retest (Wilhelm et al., 2011). The fourth is that this difference may be the consequence of the environmental indices which were present for associative recall and not present for relational recall. For relational recall, the individual was not in the main room of the ASMR in order to limit the reconstruction of the relational link through its two constituent associations, but this may

also have limited the way the context could help to activate the correct memory trace (Bayen, Phelps, & Spaniol, 2000; Davachi, 2006). To summarize these four points, we suggest that future studies should take into account pre-existing relationships between items by proposing ones with a low frequency of occurrence in everyday life or by proposing new material. We also think that it might be interesting in future studies to extend the size of the virtual room and/or to bring more diversity to the location of the items. It may also be relevant to monitor the effect of incidental relational learning and contextual benefit on recall.

The significant results of the present study complement a preceding study that used a similar set-up and observed benefits for associative, but not for relational memory after a rest period of 20 minutes (Ribeiro, Sagnier, et al., 2020). This last point is a major difference from the present study, where a full night's sleep contributed to an improvement in relational relationships (compared to a similar waking period), suggesting that the relational integrating takes both time and sleep, as suggested by Ellenbogen et collaborators (2007). Interestingly, the same memory enhancement seems to occur with a variety of item types such as abstract visual pattern (Ellenbogen et al., 2007), a picture of objects and faces (Alger & Payne, 2016; Huguet et al., 2019), a picture of scenes or object and faces (Ribeiro, Gounden, et al., 2020) and, as in the present study, spatialization of objects (Ribeiro, Sagnier, et al., 2020).

We were interested in the incorporation of the items used in the task in the content of dreams and the effect of this incorporation on memory performance. On the one hand, we showed that participants' dreams were likely to have been influenced by the study material. This result is coherent with a growing field of studies that demonstrate a continuity between what happens in daily life and night dreams (Fogli, Maria Aiello, & Quercia, 2020). Such incorporation is also present in recent studies (Plailly et al., 2019; Wamsley and Stickgold, 2019; Fogel et al., 2018; Schoch et al., 2018). For instance, Wamsley and Stickgold (2019) demonstrated that 8 out of 17 (47.06%) sleepers provided 15 dream mentation reports concerning the task material (a maze completion task). After the sleep period, these individuals had better performances than other participants in the task. Plailly and collaborators (2019) indicated that 21 out of 32 (65.63%) participants had learning-related dreams. These participants also showed better performances that those who did not report such dreams (on the visuo-spatial memory component of their task). In their study, Plailly and collaborators (2019) also performed a comprehensive literature review on studies that investigated the link between learning-related dream reports and memory performance. They found that only 5 of the 12 studies they identified showed such a link. In the present study, we were unable to assess whether incorporation led to better recall performance of the incorporated items compared to the other items; this is probably due to the insufficient number of participants involved when incorporation was 35.29% of the dream reports (6 out of 17 reports). Other studies (Nefjodov, Winkler, & Erlacher, 2016; Nguyen et al., 2013; Schredl & Erlacher, 2010) encountered similar problems, suggesting that sample size should be a concern when seeking to evaluate coincidence of memory incorporation and greater performance.

On a methodological note, we previously used a computerized, multi-platform dream journal in a similar study (Ribeiro, Gounden, & Quaglino, 2020), but for this present research, we favored a paper/pencil strategy in particular because of the simplicity of use, but also because of the widespread use of this method as a data collection tool. However, we qualitatively observed fewer dream reports than with the computerized journal as only 11 out of 27 (40,74%) participants reported one dream or more during the night in the present study while 18 out of 31 (58.26%) reported one dream or more in the aforementioned one (Ribeiro, Gounden, & Quaglino, 2020). In terms of incorporation, 14 out of 18 (77%) dreams related to the study incorporated a material in the 2020 study (Ribeiro, Gounden, & Quaglino, 2020) while it was 6 out of 11 (54.54%) in the present one. Finally, in terms of correct recall of the incorporated item, 13 out of 14 (92.86%) were correctly recalled in the 2020 study and 5 out of 6 (83.33%) in the current study. All of this suggests that a larger number of participants would have been a requirement to adequately address the effect of incorporation on memory consolidation in the present study. As a limitation related to this requirement, we did not assess how participants remembered their dreams on a daily basis or whether they were accustomed to writing down their dreams. This might have helped determine whether our lack of incorporation of dreams was due to a lack of participants or due to their familiarity with dream writing. In addition, the pumpkin dream and, to a lesser extent, the hammer dream (see Table 2) clearly show that our participants inferred that they would be asked about the experience at wake and that this is likely to have influenced their dream report (see Stern, Saayman, & Touyz, 1978).

In terms of exclusion criteria, only those who have not suffered from sleep disturbances in the last two years and who did not have photosensitive epilepsy could participate. All participants were active students at the university, in this context we considered that these rather permissive criteria could reflect the typical student population. However, the downside is a less rigorous control of our sample, especially in terms of bias possibly related to, psychiatry or sleep deprivation. On another scope and, still as a limitation, any tool that only collects dreams during a single awakening is most likely to get a small fraction of the overall dream activity; As an alternative, Schoch, Cordi, Schredl, and Rasch (2018) evaluated a collection technique based on multiple awakenings; according to the authors, this technique allows obtaining more dream content at the expense of sleep quality but without a negative impact on the sleep-related effect on memory. This technique could therefore be useful and relevant for future research and could be integrated into the computerized diary (using the alarm function) or carried out in the laboratory. On a broader level, the fact that dreams were collected from home (rather than in a laboratory) might be another major factor explaining why dream recall was low. Indeed, on one hand, dream recall performed in a home setting is valuable as a research tool and limit social desirability (see Schredl, 2002) but, on the other hand, laboratory session under polysomnography makes it possible to obtain dreams that are more representative of all sleep phases by using targeted awakenings during the desired phases. More specifically, the diary may be inclined to over-represent REM sleep dreams of the second half of the night, while the reactivations responsible for the consolidation of relational bonds seem to depend mainly on slow wave sleep, which is more represented in the first half of the night (Witkowski, Schechtman, & Paller, 2020). A laboratory setting could also have facilitated the use of vocal dream reports; vocal reports

are longer than written reports but contain fewer connections to waking life events and are less structured (Schredl et al., 2019; Casagrande & Cortini, 2008). As, we observed a rather low mean word count of 69.94 (± 42.37), we suggest that future research may emphasize more on exhaustivity and on dreamlike mentation (such as emotion or imagery) in their instruction than we did in the present study or use verbal reports. Finally, another limitation may be inherent to the study design that compared a full day wake and a full night sleep. Circadian factors limit the scope of our results as they may be differently related to the consolidation process during the day or night. As a moderation of this limitation, our present results concerning memory are in line with studies using nap designs that took place during the day (Ribeiro et al., 2020; Alger & Payne, 2016) and, are largely consistent with a previous study that employed this standard daytime wake/overnight protocol (Huguet et al., 2019).

5. Conclusions

This study proposed spatialized elements in a VR context. After a full night's sleep in a home setting, the recall performance of these elements was better than the performance obtained after a similar wake period. This benefit was present at both the associative and relational levels. Although the material studied was incorporated into the dream content, we were not able to assess the congruence between this incorporation and the recall performance of the incorporated elements. A future study could use techniques that increase the number of dream reports in order to conduct such an assessment.

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Conflict of interest

There is no conflict of interest

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Supplemental material

The R script for statistical analysis

```
#How many dreams were reported
LenghtPick = 17

#How many pick in population (to observe number of incorporation)
LenghtSimulation <- 100000

#variable to indicates whether each dream (depending on lenghtpick) present an incorporation or not
LineKick<-numeric(LenghtPick)

#Numeric number of incorporation for each simulation
ResultSim <-c(rep(0,LenghtSimulation))

#generate randomness for each pick
RandomNum <- runif((LenghtSimulation*LenghtPick), 0, 1)

#run each simulation
for (j in 1:LenghtSimulation){
  # NB0 refers to the dream reports in the population with no incorporation and NB1 refers to dreams with incorporation.
  # ---> Comment this block to select the online research 2015
  Nb0 <- 853
  Nb1 <- 79

  #---> Uncomment this block to select the online research 2015
  # Nb0 <- 5425
  # Nb1 <- 479

#For each dream of the pick (lenghtpick), determine if it was likely to be a dream with an incorporation
for (i in 1:LenghtPick){
    if ((RandomNum[((j-1)*LenghtPick)+i])<=(Nb1/(Nb1+Nb0))){
    Nb1<- Nb1-1
    LineKick[i]<-1
  }else{
    Nb0<- Nb0-1
    LineKick[i]<-0
  }

}
#how many dreams (among the X dreams picked as indicated with lenghpick) was one with an incorporation
ResultSim[j]<-(sum(LineKick))
}

#print likeliness (on /1) to observe X incorporation
print(table(ResultSim)/LenghtSimulation)
```

Transcription of the dream reports (translated from French to English).

Participant ID	Dream report	Word count
1	In Portugal, there was a big wedding and we were going to Greece on a Roadtrip.	15
2	I was working for my former employer and many things had changed: the office space, a large part of the colleagues... This place was quite different from the one I had worked in. In my dream, I particularly remember the very bad atmosphere that reigned with many complaints and remarks but I don't really remember what they were all about.	63
2	I remember I was on a safe bike ride with two old acquaintances. We had several paths and I took a different one to join them afterwards. When we stopped, there were some plasticine figurines, including one in the shape of a hand that was very realistic and that I partially destroyed.	60
3	I was in Amiens, I was in front of sorting garbage cans belonging to my apartment (in the house where my apartment is located there are none). One of my neighbors came to clean a garbage can of green waste while I was looking for the cardboard one. He tells me that there is none and directs me to another one. On my way there I meet some people I know before ending up in a park with my aunt and with, from what I understand, two of her daughters (they did not look like them at all, much younger and with a much smaller gap between them).	110
3	Quite blurry, I think that with my friend we found a dog that belonged to one of his acquaintances. We got into his **car** to what looked like a grouping, a **car** meeting. My parents joined us, argued and I wanted to go back by taking their **car** (which was by no means the one they actually have). I changed my mind and, walking home, I passed my 15-year-old brother at the wheel of a **car** and all I remember is a gunshot.	90
3	I was in a submarine, I saw a man in a maid's uniform but I had the feeling that it was me (I wouldn't know how to explain it properly, it's like seeing myself in 3rd person in a video game), I was accompanied by two other men who told me that I was claustrophobic-which I denied-but they brought me a mirror to prove that I was stomping my feet, I woke up at that moment (I felt a deep uneasiness, it was more of a nightmare).	86
4	I dreamed about the objects I had to enunciate during the study the day before and I remember the **pumpkin** in particular, It was a nightmare about what is important to me in my life, and the fear of losing it and my boyfriend was leaving me.	44
5	I was arguing with my sister in the living room of my parents' house, in the kitchen to be precise. The argument was about her going away from the family home and then an argument with a friend who was sleeping at my house, because she didn't want to get up to go through an experience that was taking place early in the morning.	55
6	I was with my mother and we were visiting a gigantic apartment. We were apparently spending a night and a day in it, it was as if we had been lent the keys. I could detail the apartment down to the object and the rooms ready, but that would be much too long. I remember that upstairs there were even pancakes that had just been made and kitchen utensils such as a blender, etc. I remember that I had to go upstairs to get the pancakes. I was absolutely thrilled to have such an apartment with so many objects at my disposal. So I called my father to tell him to do everything he could to get me the apartment but as usual he didn't seem really motivated to help me...The dream was really to explore this beautiful apartment which seemed to be in a big house. One part was "me" and the other part was the house.	148
6	it was a survival among infected beings, not zombies because they were talking but beings who wanted to kill us to infect us. It was worse than zombies because they were talking and running like us...so my dream was to run away, hide and be afraid (I often have dreams like this) I remember at the end of my dream I saw a small room with toddlers in a **toilet** in what seemed like a very small school and if at some point the infected arrived, the room would get blocked and food would come out of the wall by a mechanism to let the children survive...for a while. At the same time as the room was being shut down, you could hear "you die", instead of dying infected, they would actually starve to death... we were locked with a group of students in an amphitheater waiting for the bad guys outside to let us go and not kill us...(they were armed).	171
7	I was on my way to college with a friend but on the way I realized that I forgot my **computer**. I wanted to turn around and get it back, but two girls from the college blamed and insulted me. In the end, I couldn't get my **computer** back in time.	51
8	I dreamt that I was with a researcher (who is one of the characters in a series I am watching right now) who was recording my brain waves while I was sleeping. We had an appointment where she was analyzing my results, so I didn't sleep much per night compared to the results of one of my friends, Julie. Afterwards I told her about the experience of false memories and sleep deprivation.	70
8	It was Christmas at my grandparents' house. I was getting a great **gift** and my brother a lousy **gift**. But then we would open our common **gift** in the dining room. It was a tower to throw the baybled spinning tops (I don't know how to spell it) with a Pokémon (the big light pink chubby guy) figure on top to decorate.	56
8	I was in a school in the school life office and a high school student came to ask us where we could buy drugs. Then in the classroom I met one of the children who is in the summer camp where I work in the summer. He was very happy to see me, we hugged and then he had to leave.	61
9	I'm chasing a **hammer** in a night that seems eternal. I remember the moment I caught it I woke up. That's about it.	29

Transcription of the dream reports (translated from French to English).
(continued)

Participant ID	Dream report	Word count
10	I dreamt that I was choosing cereal for breakfast.	8
11	I dreamt that I woke up and answered this questionnaire, I just remember that there were three purple questions on my screen but I don't remember the content. I also remember waking up several times in the middle of the night and thinking that I had to answer the questionnaire (without remembering any other dream in particular) but I would go back to bed after looking at the time.	71

The names have been changed