Incorporation of complex narratives into dreaming

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Summary

Reactivation of waking neuronal activity during sleep holds a functional role in memory consolidation. Reprocessing of daytime memory in dreams might aid later memory performance in a similar way. Numerous findings hint at a link between dreaming and sleep-dependent memory processing, however, studies investigating day-residue incorporation in dreaming led to mixed results so far. In this study, we used a naturalistic learning paradigm aimed at biasing dream content by manipulating pre-sleep experience. Participants listened to one of four different audiobooks while falling asleep and were awoken several times during the night to report their dreams. Afterwards, we tested how well they remembered the content of the audiobook. We then asked three blind raters to guess, based solely on anonymized dream reports, which audiobook someone had listened to before experiencing a dream. Our findings show that dreams across the whole night and from both NREM and REM awakenings contain specific information about the content of narratives studied before sleep. Moreover, if participants dreamt of the audiobook, they retained the content better across the sleep period. Finally, memory performance was lower when the experimental situation was incorporated into dreams, regardless of the presence of audiobook content, suggesting competitive reprocessing between audiobook and experimental memory representations.

INTRODUCTION

We are asleep for approximately one third of our lives. During this time, we are cut off from the external world, yet experience vivid internal mentation, known as dreams. Generations have pondered over the meaning of this conscious experience during sleep[1,2]. It has long been known that dreaming is somehow linked to daytime experience. Freud, who studied dreams intensively, hence termed the phrase “daytime residue”[3]. Several authors refer to the correspondence between waking life and dream content as the “continuity hypothesis”[4–8], according to which salient elements, thoughts, or concerns of one’s waking experience are re-expressed in dreams. Empirical findings supported this view, as it has been shown that relevant aspects of waking life[9], as well as significant life events[10,11], affect nightly mentation. Recent research has thus started to address *why* and *how* our real-world experience becomes oneiric material.

Dreaming as an indication of memory reprocessing

A number of findings suggests that dream content might be linked to sleep-dependent memory consolidation, possibly reflecting a conscious manifestation of the neural processes that underlie nighttime memory processing[12–14]. For one, neuronal activation during sleep is directly linked to previous waking experience in animals, such that cells which were active during exploration of an environment also show stronger activity during later sleep[15,16], and fire in the same sequences as while the animal was moving about[17]. More recently, spontaneous reactivation of learning-related brain activity patterns has been reported in humans and was successfully related to subsequent memory for the studied material[18–22].

Accordingly, sleep mentation at least partially reflects novel learning. When participants played the game Tetris for extended periods before falling asleep, Tetris-related imagery was observed in reports of hypnagogic images in participants woken from the sleep onset period[23]. Kusse and colleagues[24] independently replicated this impact of the game Tetris on sleep onset imagery. In another study employing a downhill skiing arcade game before sleep, 30% of sleep onset reports showed direct incorporation of the game[25]. Similar findings were observed in studies examining the relationship between the incorporation of pre-sleep experiences into dreams during more consolidated sleep, and later memory performance[26–28]. Participants who dreamt of a spatial navigation task were better at performing the task after sleep[26,29]. Moreover, if the content of participants’ dreams was related to the category of previously studied word-picture associations, they retained these memories better across the night[27]. In an episodic memory task using odors and landscapes, Plailyl et al.[28] showed that dream incorporation of task-related content improved visuo-spatial memory for the implicitly encoded episodes. Note, however, that other studies investigating the relationship between dream incorporation and later memory performance yielded mixed results[28,30–36] (see[28] for a comprehensive summary}.

Shared properties of neural and mental reactivation corroborate the idea of a connection between the two: At the neural level, reactivation events are not precisely identical to the actual real-world encounter[37] they occur at a different time scale[38], in a

fragmented fashion, through discrete bursts of neuronal activity[39]. This suggests that memory reinstatement arises through the activation of discrete episodic units of information. In sleep mentation, dreams with relatable pre-sleep content do not replay waking experiences exactly as they occur. When an incorporation of wake-life events is observed, it is rarely the faithful reproduction of an episodic memory in its entireness[40–42].

It is unclear whether content incorporation in nightly mentation is regulated by the same neural mechanisms across all sleep phases. For instance, sleep onset incorporations seem to occur independently of the hippocampal system: Patients with extensive medial temporal lobe damage including the hippocampus, with no memory for the pre-sleep game session, could still report Tetris blocks-related imagery during sleep onset[23]. On the contrary, an intact hippocampus seems to be necessary for typical consolidated sensory-rich dreaming to occur, as well as for day-residue elaborations in dreams to appear[43–45]. This suggests that sleep onset mentation and more consolidated dreaming, and consequently the incorporation of pre-sleep elements during both phenomena, might partly rely on distinct neural mechanisms. More generally, the access to previous memory as a source of dream construction might drastically vary depending on brain connectivity and sleep state. Effective communication across memory systems strongly depends on a finely regulated milieu of neurotransmitters that shifts across sleep stages[46].

NREM and REM dreaming

While dreaming was initially attributed to REM sleep, exclusively[47,48] dream reports can be collected from all sleep stages and across the whole night[49,1,12,50–54]. Dreaming has been observed in up to 50% of cases from NREM sleep awakenings, especially from sleep stage 2[49,55,56]. Moreover, evidence showed that pharmacological REM sleep suppression does not significantly affect dream recall[57,58]. Various studies, however, reported both quantitative and qualitative differences between dream content deriving from NREM and REM awakenings. Dreaming from NREM sleep seems to be more thought-like and conceptual[59,60], whereas REM dreaming is usually described as more story-like, hallucinatory, and bizarre[61,62] and is usually associated with longer reports[63,53,64]. The distinct neurophysiological features characterizing NREM and REM sleep might explain the observed differences between REM and NREM dreaming, which also manifests in the way memory consolidation differently unfolds in the two sleep stages[65]. Studies showed that early night dreams -when NREM is predominant and ACh levels are at their lowest - more frequently incorporate recent experiences compared to late night dreams[66,67], and tend to be more episodic rather than semantic in nature[68]. Dream construction later in the night, especially during REM sleep, might instead mirror cortical networks re-organization, with dream contents thus being more associative in nature[69,70,68], and displaying more frequent semantic references[12,53]. However, the existing literature is currently not unanimous on the distinct features of NREM and REM dreaming[56,60,58], as well as their respective memory sources or incorporation dynamics across the night[71,53,60]. After combining and re-analyzing previous data, Baylor & Cavallero[40], in contrast with Cavallero et al.[53], observed higher episodic sources in dream reports from NREM compared to REM awakenings, but

could not find any stage effect for semantic memory sources. In a recent study, a higher number of mixed memory sources have been observed in both N1 and REM dreams compared to consolidated NREM dreams[67]. Importantly, ultradian cycles and other chronobiological factors also contribute to the quality of sleep mentation and memory sources selection[72–74]. Recent evidence suggests that time of the night, more than sleep stages alone, determines which memory sources more likely will contribute to dream construction across sleep periods[67]. For a comprehensive understanding of the accessibility of memory sources in dreams throughout the night, the interplay between all the above-mentioned may thus be relevant.

Incorporation of the experimental situation into dreams

In studies on dreaming, it is common to observe dream incorporation of elements related to the experimental situation[75]. Examples of recurrent themes can be the presence of the experimenter, sleeping in the laboratory, having EEG electrodes or cables attached, and being examined. Explicit references to the experiment were found in 6-32% of dreams across different studies, with the proportion rising to 32% - 68% when considering more implicit laboratory references as well[76,6] (for more studies see[75]). When present, this phenomenon may occur at the expense of the experimental manipulation itself: In early studies, pre-sleep stimuli incorporation was detected in only 5-8% of reports[77,78]. Because many argue that salient and engaging content is what mostly gets incorporated into dreams[14], the experience of sleeping in a laboratory environment while wearing an EEG device might turn out to be more notable and novel to participants than the to-be studied content. In a recent study, Picard-Deland and Nielsen[79] observed lab-related incorporation in over a third of all dreams, in almost half of participants who recalled a dream. Most experimental setting incorporations in Picard-Deland & Nielsen study were rated as prospective. This would further support dreaming's relation with reactivation mechanisms and memory processes: Neuronal activation seems to mostly prioritize goal-relevant, salient memories[80], such that consolidation would be particularly adaptive for immediate- or distant- future use[81].

Aims of this study

In the current study, we investigated whether sleep mentation reflects memory reprocessing using naturalistic stimulus material. We hypothesized that memory content encoded before going to bed should resurface in the conscious experience of participants during subsequent sleep. If it is possible to determine the content of a previous learning episode based on dream reports alone, they must contain information highly specific to this experience. To test this, we had participants listen to one of four different audiobooks while falling asleep. They were asked to remember the content well enough so they could retrieve it later. Participants were awoken several times during the night and asked to report their dreams. Afterwards, we tested how well they remembered the content of the audiobook. This procedure was repeated multiple times throughout the night. We then asked three blind raters to guess, based solely on anonymized dream reports, which audiobook someone had listened to before experiencing a dream. We further had them indicate how much information about the audiobook they detected in the dream report. Our results show that dreams across the

whole night and from both NREM and REM awakenings contain specific information about the content of narratives studied before sleep. Moreover, if participants dreamt of the audiobook, they retained the content better across the sleep period. Finally, we also examined whether the incorporation of the experimental situation into dreams interacts or competes with incorporation of the learning material as well as memory for the audiobook.

RESULTS

Audiobook-related memory is incorporated into dreams

To assess whether the specific content of the audiobook encoded before sleep is reprocessed during subsequent dreams, three independent blind raters were asked to judge which audiobook each participant had listened to before experiencing a dream, based on the transcript of the dream report and their answers to the subsequent structured dream questionnaire (see Methods). For each dream assignment, the raters also indicated their confidence in the decision using a four-point scale (0 = guessing, 1 = gut feeling, 2 = implicit indication, 3 = explicit indication). We initially considered each decision made by the three blind raters for every dream report individually. This approach was chosen to mitigate potential data loss due to ambiguous ratings when aggregating the individual raters' decisions. We compared these individual ratings to the actual experimental conditions (ground truth) and tested for the concordance of rater decisions. When considering the individual rating and comparing it to the actual experimental condition, dream reports could be successfully matched with the corresponding audiobook condition (individual ratings: $\kappa = 0.13$, $z = 3.07$, $p = 0.002$; Fig 1C). We then calculated a combined rating of all individual raters for each dream report, considering both the frequency of choice and the confidence of their rating to confirm the obtained result (see Methods). Again, we observed a significant concordance of combined ratings and the actual audiobook condition (combined rating: $\kappa = 0.2$, $z = 2.37$, $p = 0.02$; Fig 1E). The raters could decide which audiobook a person had listened to before falling asleep, based solely on the content of the night.

We then provided the blind raters with all dream reports belonging to the same participant, instructing them to repeat their rating, this time for each dream set, thus making only one rating of audiobook condition per participant. The raters were aware that each participant listened to the same audiobook throughout the night, making it possible to infer a participants' experimental condition from a single incorporation of audiobook content across all the dream reports. As expected, the raters were well able to assign the correct audiobook condition for the participants (individual ratings: $\kappa = 0.22$, $z = 3.07$, $p = 0.002$; combined rating: $\kappa = 0.44$, $z = 3.0$, $p = 0.003$; Fig. 1D-F).

Finally, we split the data according to the last sleep stage participants were in prior to each awakening to investigate dream incorporation from NREM and REM sleep awakenings separately. Most of the dream reports came directly after NREM sleep (n=35), while 11 dreams were reported after REM sleep (see Table S4 in Supplemental Information). This distribution accurately reflects the distribution of sleep stages across

the night. In the non-aggregated dataset, dream reports after both NREM and REM sleep reliably allowed raters to predict which audiobook had been listened to before (individual ratings: NREM sleep: κ = 0.13, z = 2.39, p = 0.02; REM sleep: κ = 0.312, z = 2.96, p = 0.003; Fig. 2A-B). This was confirmed for REM sleep awakenings in the combined rating (combined rating: REM sleep: κ = 0.41, z = 2.52, p = 0.01; NREM sleep: κ = 0.17, z = 1.43, p = 0.15; see Fig S2A).

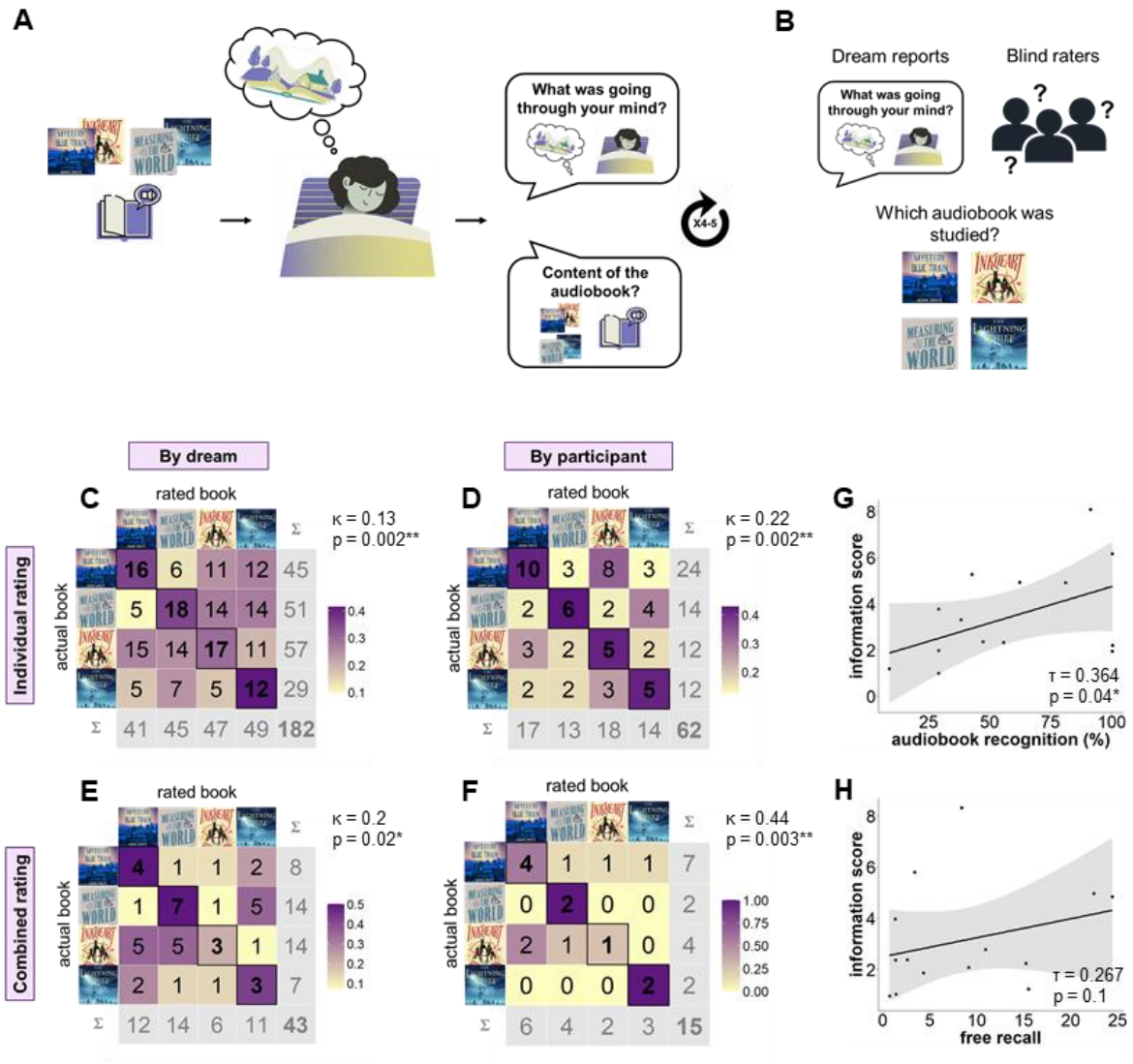

Figure 1. Incorporation of audiobook-related information into dreaming

A. Experimental design. Participants listened to one out of four audiobooks before falling asleep. Every 90 minutes they were woken up and asked to report their dreams. They were also tested for how well they could remember the previously encoded audiobook passage. The procedure was repeated across the night up to 4-5 times. **B. Method.** Three blind raters evaluated the dream reports. For each dream they were asked to guess which audiobook participants had studied, based solely on the dream reports, and to indicate their confidence, based on how much audiobook-related information they detected. **C.** Confusion matrix of listened vs. rated audiobook for individual ratings by dream. Total number of cases: 182, 1 missing value (missing rating). **D.** Confusion matrix of listened vs. rated audiobook for combined ratings by dream. Total number of cases: 43, 18 missing values (ambiguous ratings, no concordance found between the three raters). In all confusion matrices, the color scaling is determined by weighting each case according to the total number of actual instances within each audiobook

condition. Note number of correct rater decisions on the diagonal. **E.** Confusion matrix of listened vs. rated audiobook for individual ratings by participant. Total number of cases: 62, 1 missing value (missing rating). **F.** Confusion matrix of listened vs. rated audiobook for combined ratings by participant. Total number of cases: 15, 5 missing values (ambiguous ratings, no concordance found between the three raters). **G-H.** Relationship (Kendall's tau) between the amount of information reprocessed in dreams (information score) and the memory strength for the listen to audiobook passage (G: audiobook recognition in % recognized, the asterisk depicts a significant correlation, one-tailed test. H: free recall in number of words per minute of audiobook listened. The relationship was not significant in a one-tailed test). * $p < 0.05$, ** $p < 0.01$

As the time of night, beyond sleep stages, shapes which memory sources contribute to dreaming[67], we then split the data into dreams that occurred during the early night and the late night. It was possible to correctly identify the encoded audiobook based on dream reports from both the early and late night when considering each rating separately (individual ratings: early night – first two awakenings: $\kappa = 0.14$, $z = 1.98$, $p = 0.048$; late night – last two awakenings: $\kappa = 0.14$, $z = 2.66$, $p = 0.008$; fig 2C-D). Again, this was confirmed in the combined rating for reports collected in the late night, when REM sleep is predominant (combined rating: early night – first two awakenings: $\kappa = 0.18$, $z = 1.4$, $p = 0.16$; late night – last two awakenings: $\kappa = 0.24$, $z = 2.22$, $p = 0.03$; see Fig. S2B). The discrepancy in results for NREM and early sleep when considering the combined ratings may be due to consistent data loss caused by unresolvable ambiguous ratings. Since the signal was weaker for NREM sleep and the early night, this ambiguity may have rendered the effect undetectable in the combined dataset.

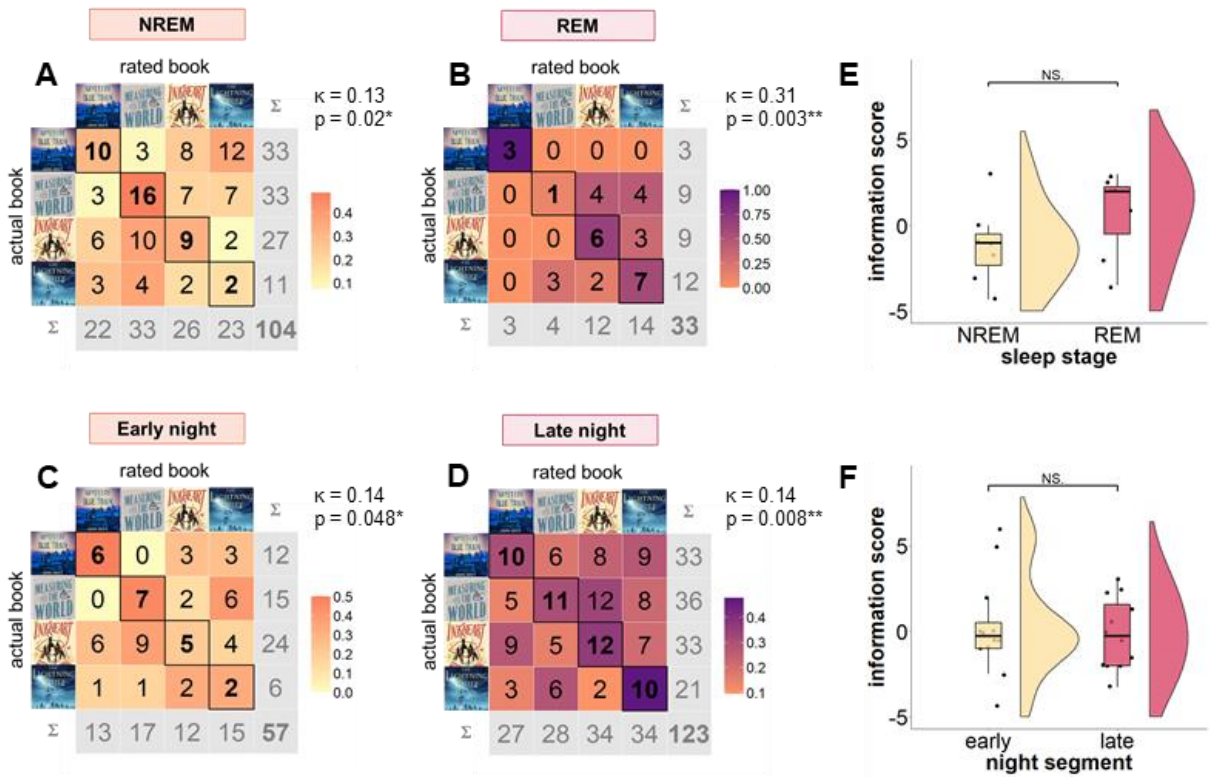

Figure 2. Incorporation of audiobook-related information into dreaming, night dynamics

A-B. NREM and REM sleep awakenings. Total number of cases: 104 and 33, 1 missing value in NREM (missing rating)**. C-D. Early and late awakenings**. Total number of cases: 57 and 123**.** In all confusion matrices, the color scaling is determined by weighting each case according to the total number of actual instances within each audiobook condition. Note number of correct decisions on the diagonal. In all confusion matrices, the color scaling is determined by weighting each case according to the total number of actual instances within each audiobook condition. Note number of correct rater decisions on the diagonal. **E.** Amount of audiobook-related information reprocessed in dreams by NREM and REM sleep awakenings. The difference is not significant (N.S). **F.** Amount of audiobook-related information reprocessed in dreams by early and late sleep awakenings. The difference is not significant (N.S). In the two plots depicting group comparisons, the horizontal black lines within the boxplots represent the median value, whereas the dots represent the single observations. * $p < 0.05$, ** $p < 0.01$

To better quantify the amount of audiobook-related information represented in dreams, an information score was obtained for each dream by weighting the confidence of the three raters by the correctness/incorrectness of their decision (see Methods). This served as a quantitative measure of reprocessing in the dream. We compared the amount of information about the previous learning episode available in each dream report between NREM vs REM, and between early sleep vs late sleep awakenings. Statistically, there was no significant difference between NREM and REM sleep ($Z = 8$, $p = 0.31$, CI [-5.67 2.50], $N_{paired} = 7$, Fig. 2E, note that participants with missing data in one of the brackets were excluded), nor between early sleep and late sleep awakenings ($Z = 41.5$, $p = 0.84$, CI [-1.67 2.83], $N_{paired} = 12$, Fig. 2F, note that participants with missing data in one of the brackets were excluded). These findings suggest that previous learning episodes resurface in a comparable fashion during conscious experience during both NREM and REM sleep throughout the whole night. However, when looking at NREM and REM sleep separately in early and late sleep, only dream reports from late sleep could be reliably assigned by the raters (late night - NREM: $\kappa = 0.183$, $z = 2.58$, $p = 0.001$; REM: $\kappa = 0.3$, $z = 2.52$, $p = 0.01$; early night - NREM: $\kappa = 0.101$, $z = 1.15$, $p = 0.245$; REM: $\kappa = 0.333$, $z = 1.53$, $p = 0.13$; fig. S3A, all results pertain to the individual ratings, see Fig. S3B for the combined rating). This suggests that while the amount of incorporated information may not vary throughout the night, incorporations might occur more frequently in dreams experienced during the late night.

Specific audiobook-related content can be detected in dream reports

In seven cases, the raters agreed on detecting indirect or direct incorporations of the audiobook content (see Table S8a-b). In all of these cases, the information could be traced back to the passage of the audiobook that was listened to during the waking time immediately before the dream occurred. In two of these cases, more remote events were additionally incorporated.

Dream incorporation benefits memory for the audiobook. If dreaming reflects memory reprocessing, dreaming of the audiobook should improve memory for its content. To test this, we analyzed whether the amount of information about the previous learning episode available in each dream report was related to memory for

the respective audiobook passage. We thus correlated the information scores, as a measure for memory reactivation, with how much of the previously encoded audiobook passage participants recognized in a later retrieval test, including only awakening for which the correct audiobook had been correctly assigned by the raters. The amount of information that was reprocessed during dreams correlated with later recognition memory for the listened audiobook passage ($\tau = 0.364$, $p = 0.04$ one-tailed, $N = 14$; Fig. 1G). Reprocessing of previous learning material through dreaming activity was thus associated with better retention of the information, which suggests an association between dreaming and memory consolidation. The same effect did not emerge for free recall performance ($\tau = 0.267$, $p = 0.1$ one-tailed, $N = 14$; Fig. 1H). The occurrence of NREM or REM sleep before each awakening, as well as the distinction between early or late night dreams, could not explain the relationship between audiobook recognition and information score (see table S7a-b for additional information).

The experimental situation gets incorporated into dreams. Two additional blind raters were asked to evaluate whether they could observe any incorporation of the laboratory environment or the experimental setting in the dreams. Contrary to our analysis on audiobook incorporation, no ground truth can be provided for incorporation of the experimental situation into dreaming, because all participants underwent the same experimental procedure. We can thus not draw statistically verifiable conclusions on whether or not an incorporation of the experimental situation actually occurred, a problem that also past research on dream incorporation has faced[75]. In a total of 61 dream reports, the blind raters identified at least one element of the experimental situation in 20 dreams, while remaining 41 showed no evidence of experiment incorporation. Dreams with incorporation of the experimental situation thus represented 33% of the total pool, which conforms to incorporation rates reported in the literature[75] (Fig. 3A; see S5A, S5B, S6, and table S9 for further details).

Audiobook vs experimental situation reprocessing compete with each other When looking at the relationship between experimental incorporation and reprocessing of audiobook-related content, we observed a tendency in dreams reactivating the experimental situation to also incorporate more audiobook content than in dreams showing no experimental situation incorporation ($U = 529.5$, $p = 0.06$, CI [-0.001, 3.0], $N = 61$, Fig 3B). Rerunning this analysis at the participant level, however, no significant association between the amount of experimental situation incorporation and audiobook incorporations was found ($\tau = 0.219$, $p = 0.3$ two-tailed, $N = 19$; Fig. 3C).

Although the association between higher incorporation of the experimental situation and incorporation of the audiobook did not consistently emerge across the above analyses, an incorporation of the experimental setting may serve as an indirect indicator of reactivation during sleep and dreaming, more generally. We thus tested whether the incorporation of the experimental setting correlates with memory consolidation, by examining memory retention across dreams with a presence or absence of experiment incorporation. We observed, contrary to our expectation, that audiobook recognition performance was significantly higher for dreams that did not include any incorporation of the experimental situation compared to dreams where raters could identify at least one element of the experimental setting ($U = 199.5$, $p =$

0.02, CI[-0.37 -0.03, N = 55; fig. 3D). A similar trend emerged after running the same analysis on the dataset aggregated at the participant level (U = 21, p = 0.075, CI[-0.47 0.08], N19; Fig. 3E), whereas no significant differences were found when repeating the same analyses on the free recall performance measure, although means show a similar direction (by participant: U = 23, p = 0.37, CI [-11.8 9.84], N = 16; Fig. 3F. By dream: U = 163.5, p = 0.1, CI [-5.75 0.58], N = 47; Fig. S7A). To further explore how dream incorporation of the experimental setting relates to incorporation of the learning material and to memory retention, we repeated all analyses only on dreams, and only for participants, for which an audiobook incorporation was reported, as well as on dreams and participants without an audiobook incorporation. A similar pattern of results emerged: regardless of whether audiobook reprocessing occurred in dreams, the presence of the experimental setting in dreams seems to impair participants' memory for the previously learned material (see Supplemental Information for further details, S7 and S8). Please note that these additional analyses often include a very low sample size and can only be considered exploratory. When considered alongside the main analyses, these findings suggest that incorporating the experimental setting into dreams exerts a competitive rather than cooperative influence on the consolidation of the learning material.

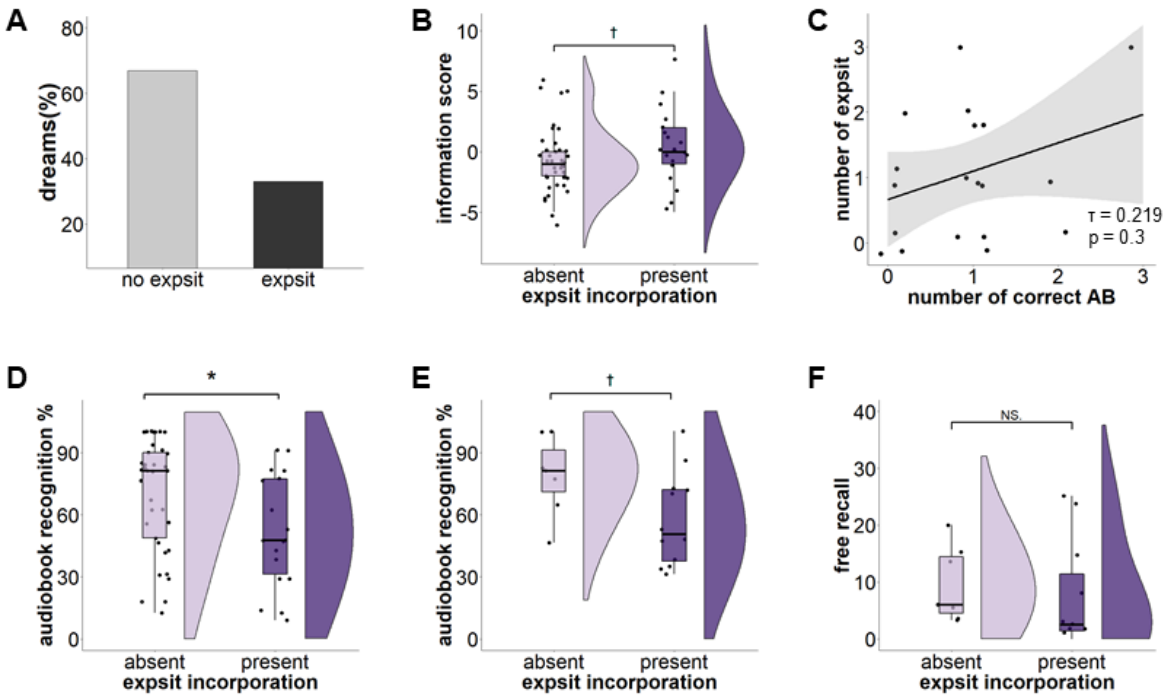

Figure 3. Incorporation of the experimental incorporation into dreaming

A. Proportion of dreams with and without incorporation of the experimental situation (*expsit*). **B.** Amount of audiobook-related content (information score) in dreams with and without *expsit* incorporation. **C.** Relationship between the number of detected audiobook incorporations (AB) and *expsit* incorporations by participant (Kendall's tau). **D.** Audiobook recognition performance for instances without and with *expsit* incorporation by dream. **E.** Audiobook recognition performance for instances without and with *expsit* incorporation by participant. **F.** Free recall performance for participants without any *expsit* incorporation vs participants that reported at least one *expsit* incorporation. The difference was not significant (N.S). In all the plots depicting group comparisons, the horizontal black lines within the

boxplots represent the median value, whereas the dots represent the single observations. Crosses indicate a trend in the group comparison ($p < 0.1$), * $p < 0.05$.

DISCUSSION

Dream incorporation of the learning material and memory reprocessing

We find that blind raters can correctly assign which audiobook someone had listened to before falling asleep, based solely on the dreams they reported during the night. The content of the audiobook thus resurfaced in dream narratives during consolidated sleep. Importantly, participants who incorporated more audiobook content into their dreams also had better memory for the audiobook passages they studied before. Findings regarding the association between dream incorporation and memory performance have been mixed (see[28] for an overview). Our results support previous studies that reported a positive effect of dream incorporation on memory retention for two different kinds of learning material, word-picture learning and spatial navigation performance[27,29]. We now show that also episodic narratives, content similar to our continuous waking experience, resurface in sleep mentation and that this incorporation is related to how well memory for these stories is retained. Importantly, the benefit of dream incorporation mirrors the memory benefit of spontaneous neural reactivation of learning-related activity patterns[18–22]. Indeed, we observed that the neural activity during REM sleep was associated with the retention of the audiobook content[82]. Moreover, participants who incorporated the audiobook during the night showed a higher neural reactivation index. Taken together, these findings support the idea that offline neural reprocessing surfaces in conscious experience during sleep, thereby contributing to dream construction.

A novel paradigm to study dreaming

For this study, we took a novel approach to study memory incorporation into dreaming. Similar to Schoch et al.[27], we explicitly manipulated the content of learning material to bias memory processing during sleep, and consequently in sleep mentation. We extend that work by showing that also complex naturalistic stimuli, i.e., the narratives of audiobooks, become incorporated into later dreams. Contrary to previous studies, where participants were asked to retrospectively rate the similarity of their dream reports with their daily activities in the days or weeks preceding the experiment[40,41,72,83], more and more recent studies employ independent raters who are instructed to judge the reported dream contents[84,26,29,27,28]. Our study employed three independent and blind raters to make alternative forced-choice judgements about the content of the previous learning material, allowing us to verify their ratings against a ground truth. This makes it possible to directly test the hypothesis whether learning content is incorporated into dreams during the night and investigate sleep mentation as a marker of memory reactivation.

Incorporation rates in studies employing independent raters are lower, and are necessarily more conservative than incorporation rates in studies where participants rate concordance of waking life and dreams. Contrary to other approaches, alternative forced choice judgements create noise in the data in cases where no memory

incorporation occurred in dreaming and raters have to guess conditions. It is therefore remarkable that we were able to detect a memory incorporation signal in dream reports at a level that exceeds chance.

Characteristics of dreams in different sleep stages and at different times of the night

Learning-related information was reflected in the content of dream reports originating from both NREM and REM awakenings, without appreciable differences between early and late night. This seems to contrast previous observations ascribing incorporations of recent memories and waking-life experiences mostly to the early night[66,68,67], and findings from reactivation of learning-related neural activity in animals that report that the strongest reactivation of learning activity occurs during the first 30 min of (NREM) sleep[85]. Our multiple awakening paradigm entailed sequential encoding of the audiobook throughout the night, thus ensuring temporal proximity to the originating wake experience during all times of the night. In all cases when our blind raters detected an audiobook-related incorporation, the reactivated content could be traced back to events in the audiobook section presented immediately before the sleep period in which the dream occurred. Moreover, the amount of incorporated information did not differ between sleep stage or time of the night. This indicates that temporal proximity to the encoded experience may be a more decisive factor in whether information gets incorporated into dreams than sleep stage or time of the night. However, when analyzing incorporations from NREM and REM awakenings during early and late sleep, only late-sleep dream reports were reliably linked to the learning condition. This suggests that while the amount of incorporated information remains consistent, incorporations or detectable dream content may be more frequent in late-night dreams. Higher incorporation scores late during the night might be attributable more to the ability to recall dream content than to an influence on dream construction itself. When examining the relationship between dream length and information score, however, there was no significant correlation (see Supplemental Information, fig. S9).

Note that in our study, we did not characterize the memory sources of the dream reports (e.g., autobiographical, semantic) through systematic coding, thus making it impossible to distinguish these qualitative features of dreams and compare them between NREM and REM sleep awakenings. Instead, our method relied on forced choice decisions made by blind raters who indicated what sources of information they based their rating on (guess, gut feeling, indirect or direct incorporation), and thus in which way content from the audiobook was incorporated into dreaming. Only 2% of the dreams contained an explicit incorporation of the audiobook-content, in line with previous evidence reporting episodic incorporation into dreaming only 2-4% of the time[40–42]. In 10% of the cases, raters could instead detect indirect references in the dream report which could be traced back to specific occurrences or themes in the book. While explicit dream references refer to unambiguous episodic events that occurred in the book narrative, implicit references encompass a broader spectrum of mixed memory sources, including semantic similarity, as well as related autobiographical sources. Our findings align with other studies that made no distinction in incorporation type[27], which similarly found no significant difference in incorporation rate between

NREM and REM awakenings. Furthermore, it is not possible to determine when dreaming exactly occurred prior to each awakening. Our analyses were performed and results are interpreted under the assumption that all dreams occurred during the few minutes before waking up. For this reason, our findings comparing dream reports from NREM and REM awakenings do not rule out the possibility that either memory incorporation or emotional tone leaked into NREM or REM dream awakenings from preceding sleep stages. More generally, when no stage suppression or manipulation is operated by experimental design[58], results on the effects of sleep stages on dreaming need to be interpreted with caution.

Dream incorporations of the experimental situation

In our study, approximately 30% of the dream reports contained incorporations of the experimental situation. This is in line with the dream incorporation frequency usually reported, ranging between 30-70% when both explicit and implicit elements of the experimental situation are considered[75]. From our analysis, a trend emerged that dreams reporting audiobook-related incorporations often also contained at least one element of the experimental situation participants underwent. This raises the question whether some participants are overall 'stronger incorporators' of waking-life elements[36]. When examining the association between the number of audiobook- and experiment-related incorporations for each participant, however, we were not able to observe any significant relationship. While our findings do not allow definitive conclusions about the relationship between laboratory and stimulus-related dream incorporations, future studies should explore this question in greater depth.

Spending the night in a sleep laboratory and performing an experimental task is a salient, novel experience, which may lead to competition between episodic features of this personal event and the audiobook-related content for neural resources during night time reprocessing[86,87]. If this were the case, audiobook-related memory would be expected to be worse when the experimental situation is incorporated into dreams. Conversely, since the laboratory setting provides the broader context for studying the learning material, its incorporation into dreams might instead reflect the general reactivation of pre-sleep experience. Thus the incorporation of the experimental situation may also be positively related to consolidation of the studied material[88–91] (for a review, see[92]). Recent findings showed that dreaming of the laboratory setting is associated with better performance on a sign language learning task[93], supporting the latter view. Our results, however, seem to indicate a competitive, rather than cooperative, influence of laboratory setting incorporation on retention performance for the previously learned narratives. This incongruence may stem from the different tasks, and consequently, memory systems recruited in the two studies. Visuospatial and sensorimotor tasks, such as sign language learning, may be more strongly tied to the laboratory environment where the learning occurred. In contrast, complex narratives likely immerse the participant in a sensory-rich learning experience where the primary context may become the setting of the story itself. Instead of one coherent representation, this might favor the formation of two distinct memory representations

in temporal proximity, i.e., the experience in the laboratory and the experience in the narrative, leading to a more intricate interaction during offline reprocessing depending on the strength of both representations at encoding (see[92]). Examining the interplay of learning content and experimental setting incorporation and how they relate with memory performance across different kinds of task, particularly considering how relevant the experimental context is to task completion, may further elucidate the nature of this interaction.

Limitations

It is important to note that due to the overall small sample size, some of our analyses may be underpowered. Effects that only emerged subtly in our study should be further examined in larger samples, e.g., the relationship between dream incorporation and memory retention. Furthermore, in the multiple awakening paradigm used in this study, participants underwent encoding multiple times throughout the night. On the one hand, this approach allowed us to investigate whether the temporal proximity between learning and dreaming influences which content is more likely to be incorporated into dreams. Except for two instances, the incorporated content only referred to the most recently listened portion of the audiobook. On the other hand, this method does not provide a baseline measure of participants' initial memory strength before sleep, making it more difficult to determine who benefitted from audiobook-related dream incorporation.

CONCLUSIONS

Our results indicate that dreams reflect internal memory reactivation processes. Both dreams from NREM and REM sleep, as well as from the early and late night contained information about studied audiobook narratives, indicating that memory incorporation is a universal process, occurring during all sleep stages and regardless of when sleep occurs. The more information about the audiobook could be detected in dreams, the better participants retained their memory for the narrative across the sleep period. Our experiment was designed to mirror paradigms investigating neural reactivation in humans, making it possible to relate findings on dream incorporation and neural reactivation[21,82,22,94]. Indeed, a paper assessing neural reactivation in our paradigm was able to detect reprocessing of audiobook content in our participants' electrical brain activity during sleep[82]. Intriguingly, neural reactivation was stronger in participants who dreamt of the audiobook, lending further strength to the idea that dreaming at least in part reflects nighttime memory processing. While it is becoming more and more apparent that memory reprocessing, consolidation, and dreaming are strongly intertwined, it is still unclear how they interact, what determines which memories will resurface in dreaming, or which type of processing these fragmented memories undergo. With recent methodological advances, future research incorporating larger sample sizes and preregistered hypotheses may soon be able to address these gaps[94].

METHODS

Participants

20 subjects (10 male) aged 20 – 30 (25.5 ± 2.7 [mean ± s.d.]) participated in this study. Participants were healthy, non-smokers, and did not ingest any alcohol, caffeine or medication other than oral contraceptives on the days of the experiment. The participants reported sleeping between 6 and 10 hours per night, had a regular circadian rhythm, and were not extreme morning or evening chronotypes, measured by the Munich Chronotype Questionnaire (MCTQ)[95]. They had no shift work or long-distance flights during the six weeks preceding the experiment and did not have any sleep-related pathology. All participants were right-handed, as confirmed by the Edinburgh Handedness questionnaire[96]. Only participants who reported to frequently recall dreams (at least three dreams per week) were selected for this study. The experiment was approved by the local ethics committee (Department of Psychology, Ludwig-Maximilians-Universität München). Informed consent was obtained from all subjects.

Experimental Procedure

All participants visited our laboratory twice, once for an adaptation night to become familiar with the experimental procedure and environment, and again for the night of the actual experiment. Subjects had to indicate beforehand whether they had read or watched the movies of the following books: Cornelia Funke – Inkheart, Agatha Christie – The Mystery of the Blue Train, Daniel Kehlmann – Measuring the World, Rick Riordan – Percy Jackson & the Olympians: The Lightning Thief. None of the participants admitted to the study were familiar with the audiobook content. On the day of the experiment, participants fell asleep while listening to one of the four audiobooks. The books were randomly assigned to the participants. They were instructed that they should listen closely, such that they would be able to report what occurred in the audiobook passage upon awakening, but to fall asleep when they felt the need. At the same time, a tone played every 15 seconds. Participants were asked to press any key on a computer mouse in response to the tone to confirm they were paying attention. The audiobook was turned off by the experimenter once they reached consolidated stage 2 sleep and stopped responding to the tone. The audio was played through external speakers at a volume of 45 dB ± 2.92 dB (mean ± SD), measured using a sound meter at the approximate location of the participants' head in bed, ensuring the story was audible. The participants were awoken by the experimenter entering their room and addressing them by name after approximately one cycle (87 ± 16 min [mean ± SD]). If that was not sufficient to rouse the participant, the experimenter touched them lightly on the arm while addressing them again. Participants were informed of this procedure. Upon awakening, they were questioned about their conscious experience immediately before waking up (collection of dream reports, see below for details) and subsequently asked to retrieve the audiobook passage they had listened to before falling asleep (memory retrieval, see below for details). They were then instructed to go back to sleep, resuming to listen to the same audiobook at the point where they had left off before falling asleep, again paying close attention such that they could report

what happened in the audiobook upon awakening. This procedure was repeated up to five times per night. The audiobook was played from beginning to end. Participants listened to an average of 35 ± 28 min [mean ± SD] minutes of audiobook before falling asleep. Two participants finished their audiobook before the experimental night was over. They continued the experiment listening to a different, additional audiobook, otherwise following the same procedure as reported above.

Descriptives

Each participant was awoken multiple times throughout the night (4.1 ± 0.44 [mean ± SD], N = 20). Out of 82 awakenings, 61 dream reports were collected, making the dream report rate 74%. On average, participants had 3.1 ± 1.7 [mean ± SD] of total dreams during the night. On some occasions, participants reported more than one dream after being awoken. One participant had no dreams to report throughout the night and was thus excluded from all analyses (remaining N = 19). During an average sleep period (across all awakenings), they were awake for 7 ± 2 minutes, spent 8 ± 3 minutes in sleep stage 1 (S1), 29 ± 12 minutes in sleep stage 2 (S2), 14 ± 7 minutes in slow wave sleep (SWS), and 16 ± 9 minutes in REM sleep, giving an average total sleep time of 67 ± 13 minutes [mean ± SD]. For additional details, see Supplemental Information (fig. S1, tables S1, S2, S3, S4).

Dream reports

After each sleep period, participants were questioned about their conscious experience at the moment of awakening. Conscious experience at awakening is considered to reflect the content of the dream that is experienced during sleep immediately before[84]. Reports of sleep mentation were collected in a standardized manner by asking participants repeatedly, up to three times, what went through their mind immediately before waking up, and to report any conscious experience they might have had. If the participants were able to remember any conscious experience from the preceding sleep period, we instructed them that they should proceed to give a detailed report on who participated in the dream, where the dream was set, and what happened in the dream. We recorded their full dream report, asking up to three times “Can you recall more?” We then proceeded to inquire further details regarding the dream content with a standardized dream questionnaire: Who had been part of the dream? Where had the dream taken place? What happened in the dream? What was the perspective of the dream? Did the participant experience any emotions while dreaming? What would they name as the central element of their dream? Only questions that were predefined in this questionnaire were used to assess the content of the participant’s dream. All participants had to answer all questions, but had the option to indicate that they had no memory for any particular question. Questions were always asked in the same standardized order.

Memory retrieval

After reporting their dreams, participants had to retrieve the audiobook content. They were first asked to freely recall what happened in the audiobook passage they had listened to before going to bed. To assess recognition memory, participants were then aurally presented with segments of the audiobook they had previously listened to and asked to indicate, for individual sentences, whether they remembered having listened to it earlier (*certainly yes, do not know, certainly not*). The whole questioning procedure was recorded on tape and later transcribed. The transcribed text of the free memory recall was redacted for clarity and to make length respective to informational detail as comparable as possible across participants (removal of unnecessary words, use of simple active language). Free recall performance was assessed as number of words in the free recall divided by the time (in minutes) listened to the audiobook while participants were awake. Recognition performance was assessed as the audiobook runtime of yes responses divided by the audiobook runtime while awake. After the dream recall and audiobook retrieval, participants fell asleep while listening to the subsequent part of the same audiobook. All participants listened to at least 5 minutes of the audiobook before falling asleep (ranging from 6 to 121 minutes).

Polysomnography

Sleep EEG was recorded using a 128-channel active Ag/AgCl electrode system (ActiCap, Brain Products, Gilching, Germany) with a sampling rate of 1 kHz and a high-pass filter at 0.1 Hz. Electrode placement followed the extended international 10–20 system (Jasper, 1958). For sleep staging, the recordings were segmented into 30-second epochs, and linear derivations were computed (EEG: C3 and C4 referenced to the contralateral mastoids, vertical and horizontal eye movements, and EMG activity). Sleep stages were assessed using electrodes C3 and C4 based on standard criteria, with two independent raters conducting the evaluation and a third resolving any discrepancies.

Analysis

All statistical analyses were performed using RStudio 2021.09.1, using two-tailed tests for significance, if no a priori hypotheses indicated the use of one-tailed tests.

Dream rating. Audio recordings of the dream recall and retrieval of the audiobook content were transcribed for the analysis. Three independent blind raters were asked to match the written dream reports with one of the four audiobook conditions. They were blind to the audiobook condition and all subject details, uninvolved in data collection or audio transcription, but had thoroughly studied the content of each audiobook, having both listened to them and read the text versions in detail (which were adapted to match the exact content of the audiobooks). Therefore, they had a detailed knowledge of the four narratives. While performing their ratings, they had access to both the audiobooks and the text versions, with timestamps for each page to facilitate comparisons between the text and the audiobook timing. Additionally, they

were provided with information for how long participants had listened to the audiobook, enabling them to compare this with the timestamps in the text version. For the rating they were presented with single dream reports in a randomized order *(per dream report rating)*. Each report included the transcribed version of the free dream recall and additional information about the content of the dream collected through a standardized cued dream questionnaire. Information in the transcribed audio recording that could indicate that dream reports belonged to the same participant or revealed the participant's identity was removed beforehand (e.g. "like in my previous dream about…"). For their rating, they could thus only take into account information from one report at a time. The raters were asked to rate the confidence of their decision according to how much information about the audiobook they detected in the dream report (0 = guessed, 1 = gut feeling, 2 = implicit indication, 3 = explicit indication). If raters stated to have traced an implicit or explicit indication for the listened audiobook, they were asked to report which part of the audiobook narrative was incorporated. Please note that not all narratives of dreams for which ratings indicated a direct or an indirect incorporation could be linked to specific events in the audiobooks. For a full list of dreams with indirect and direct incorporations that could be traced to specific events in the audiobooks, see Supplemental information (Table S8a-b). These dreams represent all direct and indirect incorporations for which all three raters agreed there was an incorporation. To assess whether the information that is reprocessed during dreams indeed stems from the most recently listened audiobook passage, we examined the temporal origin of the explicit and implicit references to audiobook content that could be traced to specific sections of the audiobook (Table S8b).

Concordance analyses. The agreement between rated and the actual audiobook was assessed across the whole night by using Cohen's kappa (concordance measure between the rated condition and the ground truth). If there is significant concordance between the rated and the actual conditions, information about the learning material must be present in the dream reports. Concordance measures are expected to be low in these analyses due to anticipated variability in memory incorporation across dream experiences, possible inaccuracies in the raters' recall of narratives, and differences in their criterion for identifying distorted forms of the audiobook narrative in the dream reports. Two participants listened to two audiobooks throughout the night because of long wake times. In these cases, ratings were considered correct when the rated audiobook had been presented prior to any previous awaking during the night.

Individual ratings. In a first analysis, each decision made by the three blind raters for every dream report was considered individually (a total of 182 ratings for the 61 obtained dream reports). The inter-rater agreement was positive and significant, indicating they based their ratings on similar information in the dream reports ($\kappa = 0.236$, $z = 5.48$, $p < 0.001$). Please note that given the noise sources stated above, also inter-rater agreement is expected to be low in this analysis.

Combined rating. In a second analysis, the ratings for each dream report were combined across raters to obtain one final decision on which audiobook had been previously listened to. For this, the subjective confidence of ratings was taken into account. For each dream report, confidence scores were summed for identical ratings

across raters. The audiobook category reaching the highest total confidence score was selected as the consensus rating for that dream report. This process resulted in 43 consensus ratings for the 61 obtained dream reports. If two books had the same total confidence, no consensus was reached, and the report was treated as missing value.

Effects of sleep stage and time of night. The same analyses were then repeated after dividing the dataset by the last sleep stage experienced prior to awakening (NREM and REM sleep) and after dividing the dataset by early and late sleep awakenings. Sleep periods in which participants were woken up from S2 or SWS were considered NREM awakenings, and sleep periods when participants were awoken from REM sleep REM awakenings. The first two awakenings of the experimental night were considered early awakenings while the last two awakenings of the night for each participant were considered late awakenings. Thus, when a participant was woken up five times, the third awakening was not considered in the early vs. late awakenings analyses. Contingency tables were generated to visualize results for all analyses.

Per participant rating. In an additional, consecutive but separate round of dream ratings, the raters were presented with the collected dream reports of all individual participants, de-blinding which dream reports belonged to the same participant (and thus the same audiobook condition). Again, they had to rate which audiobook a person had listened to throughout the night.

Incorporation strength. We calculated a measure for the amount of information about the previously listened audiobook represented in later dream content. For each dream report, we summed the confidence ratings provided by the three raters which, based on the instructions, reflect the extent of information related to the audiobook content. Confidence statements for correct decisions were entered as positive values, statements for incorrect decisions were entered as negative values into this reprocessed information score. The Wilcoxon signed rank test was used to test potential differences in the amount of dream incorporations between NREM and REM, as well as early and late sleep awakenings. NREM awakenings included all the awakenings in which participants woken up from S2 and SWS. For this analysis, only participants with dream reports from both NREM and REM awakenings were considered, resulting in a reduced dataset with dream report-related data paired by sleep stage for each participant (remaining N = 7). The data from the first two and last two awakenings of the night were averaged for each participant to obtain a final information score for early and late night. For this purpose, participants without any awakening in the first or second part of the night were excluded from this analysis (remaining N = 12). Given the low sample size, these comparisons should be interpreted with caution.

Correlations with memory performance. Dream incorporation of previous learning material has been associated with better memory for the content in previous studies[27,29]. We thus tested whether dream incorporation is *positively* related with memory for the audiobook. We used a non-parametric correlation coefficient that is suited for small samples (Kendall's tau, one-tailed test for $\tau > 0$) to correlate memory performance for the listened audiobook passage, measured as percent correctly

recognized audiobook content, with the amount of information about the book reprocessed during dreams in that sleep period. For this analysis, only observations with a positive information score were included (N = 14). The same test was then repeated for the free recall performance. Participant's dreams belonging to the same awakening were kept as separate dreams.

We then used a linear regression model (*lm* function) to test whether the occurrence of NREM or REM sleep before each awakening could explain the association between dream incorporation and memory performance. In our model, audiobook recognition was entered as the dependent variable, while information score and sleep stage were entered as possibly interacting predictors (model used: *lm(audiobook_recognition ~info_score*last_sleep_stage*). The variance inflation factor (VIF) analysis yielded a score of 3.95 for the variable last sleep stage and 2.20 for info score, indicating no severe collinearity issues that would justify excluding the model. Following the same rationale, we tested whether early or late night could predict the memory benefit for instances with stronger incorporations of the audiobook (model used: *lm(audiobook_recognition ~info_score*night_segment*). Given the low sample size, these correlations and results of the linear regression model should be interpreted with caution.

Laboratory setting incorporation. For each dream report, we also evaluated whether we could detect any incorporation that was related to the experimental situation (experimenter, EEG cap, experimental beds, experimental procedure, etc.). Two separate raters independently evaluated the presence of experimental incorporation into dreams (1 = *expsit yes*, 0 = *expsit no*). In case of disagreement between the two raters, a final consensus was reached through discussion, following an approach previously employed, when quantifying dream incorporations[28]. An example of absent, implicit and explicit laboratory dream incorporation is provided in the Supplemental Information section (table S9). We first computed a Wilcoxon signed-rank test to compare the amount of audiobook-related information (information score) reprocessed in dreams with and without *expsit* incorporation. For each participant, we then calculated the overall amount of dreams with experimental situation incorporation and dreams with correct audiobook identification, and used Kendall's Tau to test the relationship between the two measures. We additionally correlated, for each participant, the overall ratio of dreams showing *expsit* incorporation over dreams without any, with the overall ratio of dreams showing audiobook incorporation divided by the number of dreams where no audiobook incorporation was reported. Since it remains unclear whether the incorporation of the experimental setting interferes with or facilitates content incorporation[75,79], we conducted two-tailed tests for these analyses. To investigate the association between incorporation of the experimental situation and consolidation, we first compared the memory performance —measured by both audiobook recognition and number of freely recalled words—between dreams that included incorporation and those that did not. We repeated the same analysis on the dataset aggregated by participants who reported at least one experiment incorporation across all dreams versus participants without incorporations. Second, we separated both datasets (once by dream and once by participant) based on whether

at least one incorporation of the previously listened-to audiobook was present or not, and again compared the difference in audiobook recognition and freely recalled words between instances with and without incorporation of the experimental situation. Note that Wilcoxon rank sum tests were used for all these analyses instead of Wilcoxon signed rank, as using a paired version of the dataset with aggregated data points would have resulted in consistent data loss (see Results for the different sample sizes for each analyses). However, we also performed Wilcoxon signed rank test for those participants where it was possible to pair memory performance by awakenings with and without experimental situation incorporation (N = 8). Finally, we wanted to examine the temporal occurrence of such incorporations across the night and sleep stages. The McNemar test was used to compare the frequency distribution of dreams with and without *expsit* between early and late sleep (N = 12), as well as between NREM and REM sleep awakenings (N = 7). Given the low sample size, the results of these analyses should be interpreted with caution.

Dream length and audiobook incorporation. To test whether the length of dream reports determined the amount of audiobook-related information blind raters detected in dreams, we calculated Kendall's Tau. Dream length was quantified as number of words in each dream report. Dream reports were redacted such that they only included content referring to the dream experience.

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AUTHOR CONTRIBUTIONS

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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Supplemental Information

Incorporation of complex narratives into dreaming

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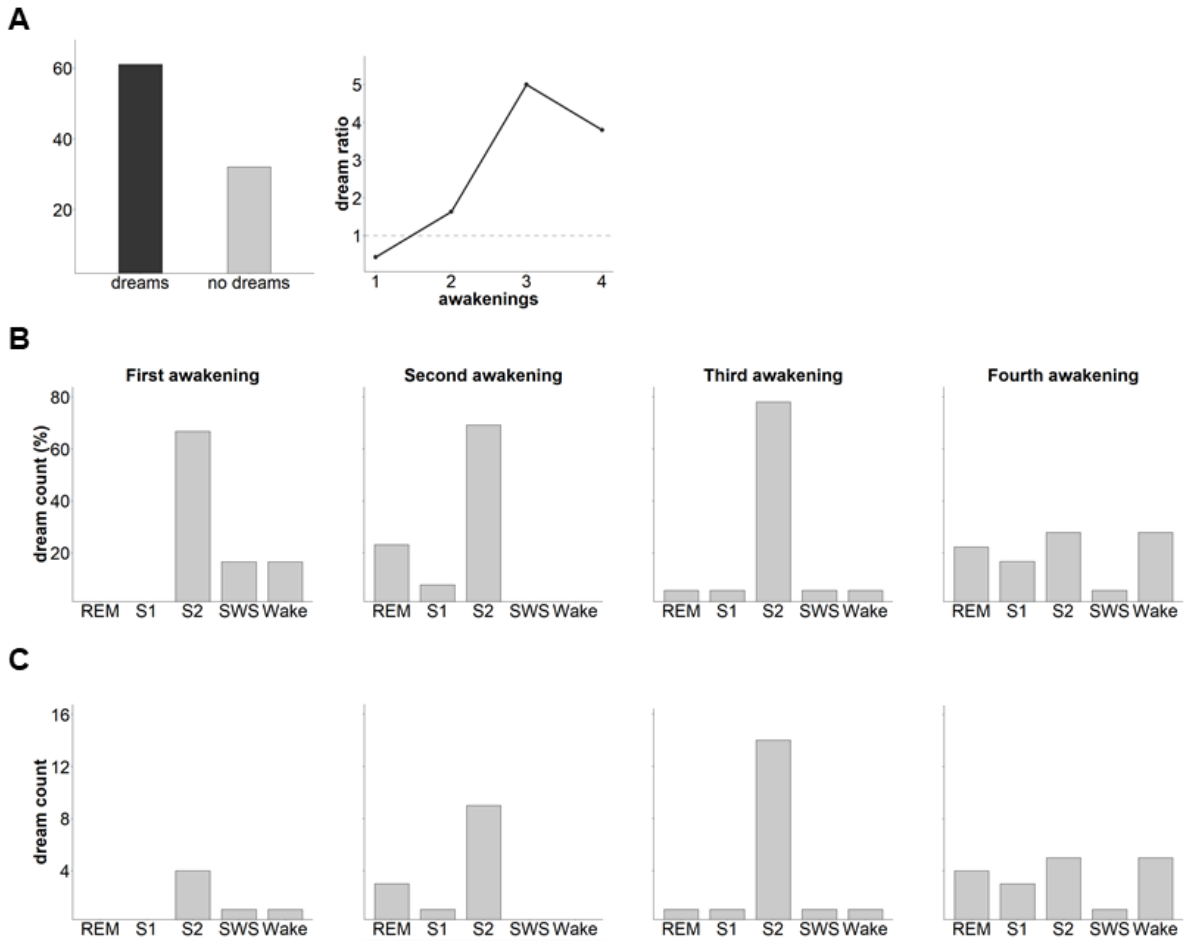


Figure S1. Distribution of collected dream reports and no dreams reported, across awakenings and sleet stages.

A. Proportion of dream reports collected throughout the whole night in contrast with no dreams reported. The bar graph on the left displays the absolute numbers whereas the graph on the right depicts the ratio of dreams vs no dreams reported across awakenings. **B.** Last sleep stage experienced before reporting a dream, from the first to the fourth awakening, in percentage. **C.** Last sleep stage experienced before reporting a dream, from the first to the fourth awakening, absolute numbers.

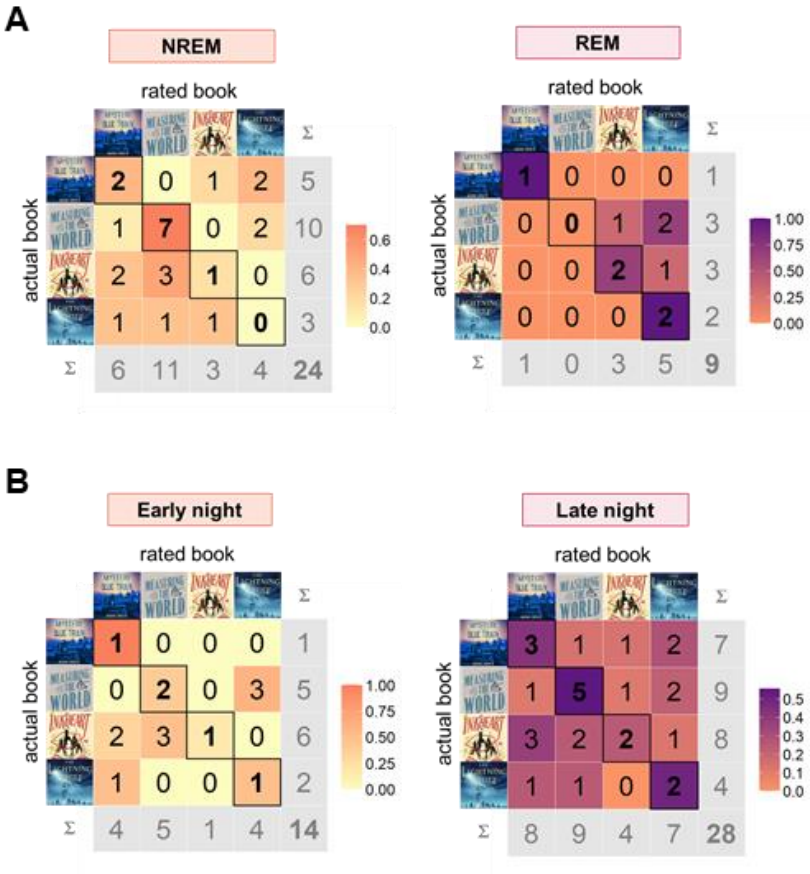


Figure S2. Confusion matrix of listened vs. rated audiobook for combined ratings, night dynamics.

A. NREM and REM sleep awakenings. NREM: κ = 0.172, z = 1.43, p = 0.15; REM: κ = 0.41, z = 2.52, p = 0.012. Total number of cases: 24 and 9, 11 missing values in NREM and 2 in REM (ambiguous ratings). **B. Early and late awakenings**. Early awakenings: κ = 0.176, z = 1.4, p = 0.16 ; Late awakenings κ = 0.237, z = 2.22, p = 0.03. Total number of cases: 14 and 28, 5 missing values in early awakenings and 13 in late awakenings (ambiguous ratings, no concordance found between the three raters).

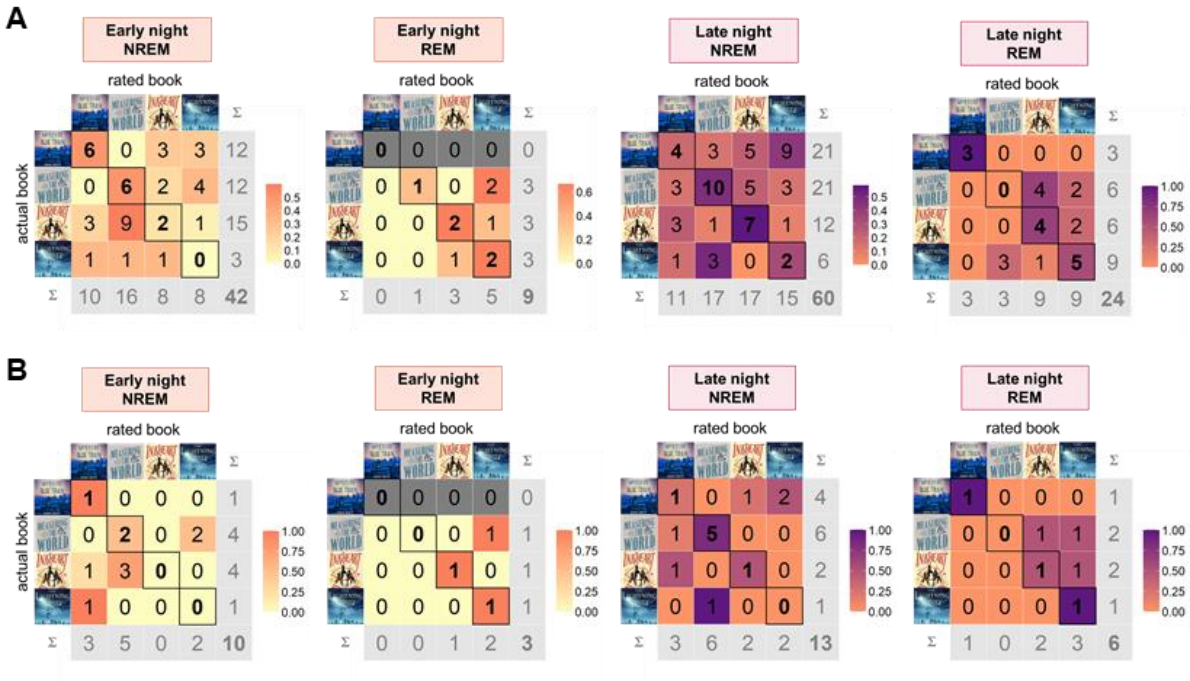


Figure S3. Confusion matrix of listened vs. rated audiobook for NREM and REM awakenings in individual and combined ratings, split by early and late night.

A. **Individual rating.** From left to right: **Early night NREM,** κ = 0.101, z = 1.15, p = 0.25, total number of cases 42; **Early night REM**, κ = 0.333, z = 1.53, p = 0.13, total number of cases 9; **Late night NREM,** κ = 0.183, z = 2.58, p = 0.001, total number of cases 60; **Late night REM:** κ = 0.304, z = 2.52, p = 0.012, total number of cases 24. **B. Combined rating.** From left to right: **Early night NREM,** κ = 0.06, z = 0.467, p = 0.64, total number of cases 10, 3 missing values (ambiguous ratings, no concordance found between the three raters); **Early night REM**, κ = 0.5, z = 1.5, p = 0.13, total number of cases 3; **Late night NREM,** κ = 0.322, z = 1.88, p = 0.06, total number of cases 13, 8 missing values (ambiguous ratings, no concordance found between the three raters); **Late night REM:** κ = 0.357, z = 1.87, p = 0.06, total number of cases 6, 2 missing values (ambiguous ratings, no concordance found between the three raters);

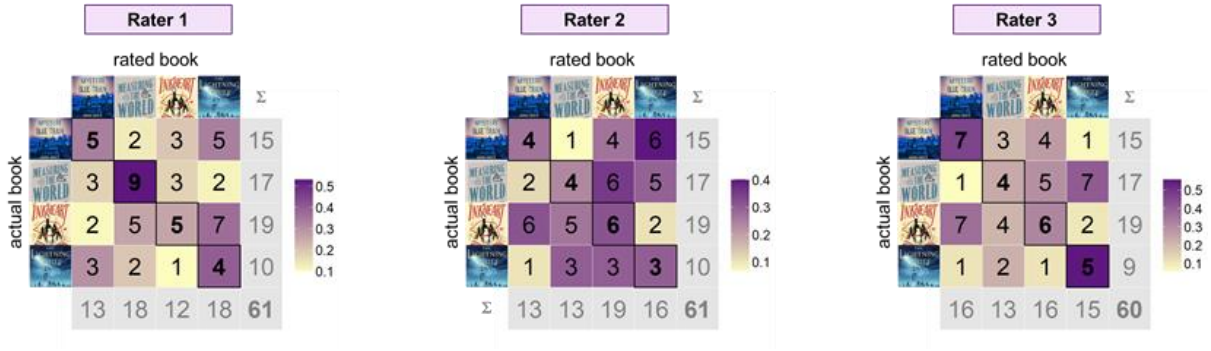


Figure S4. Dream rating analysis by single rater.

Confusion matrix of listened against rated audiobook for each rater. **Rater 1:** κ = 0.176, z = 2.45, p = 0.014, total number of cases 61; **Rater 2:** κ = 0.036, z = 0.49, p = 0.62, total number of cases 61; **Rater 3:** κ = 0.156, z = 2.11, p=0.035, total number of cases 60, 1 missing value (missing rating).

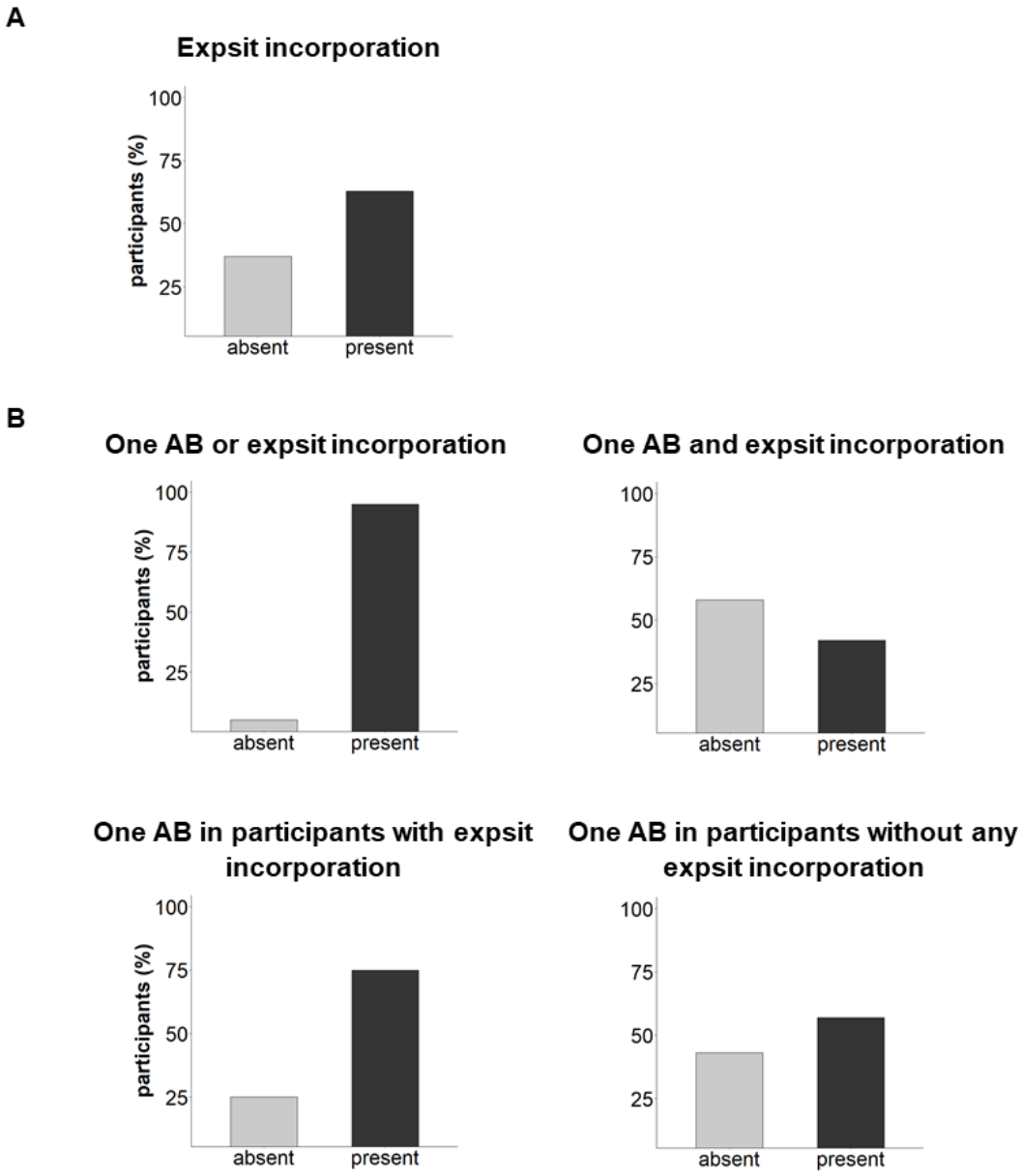
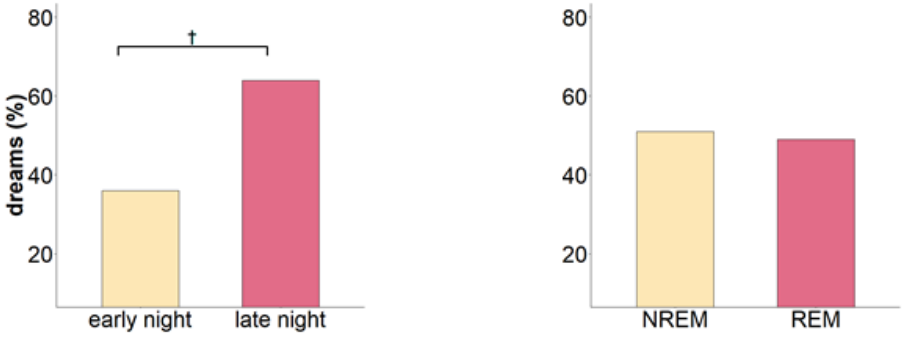


Figure S5. Distribution of incorporation of the experimental situation in dreams across participants.

A. Proportion of participants with and without incorporation of the experimental situation (*expsit*) into dreams. **B. From top left to bottom right: (1)** Proportion of participants with at least one audiobook incorporation (*AB*) or experimental situation (*expsit*) incorporation into dreams; **(2)** Proportion of participants with at least one audiobook incorporation (*AB*) and experimental situation (*expsit*) incorporation into dreams; **(3)** Proportion of participants with and without audiobook incorporation (*AB*) from the pool of participants who reported at least one experimental situation (*expsit*) incorporation into dreams; **(4)** Proportion of participants with and without audiobook incorporation (*AB*) from the pool of participants who did not report any experimental situation (*expsit*) incorporation.



Early night	Late night	-	NREM	REM
4	16	**Expsit**	13	4
15	26	**No expsit**	22	7

Figure S6. Distribution of dreams with and without incorporation of the experimental situation, night dynamics.

Bar graph on the left: Distribution across early and late awakenings in percent. **Bar graph on the right:** Distribution across NREM and REM awakenings in percent. **Table:** Distribution across early and late awakenings ($\chi 2 = (1, N_{paired} = 12) = 3.2$, $p = .07$), as well as NREM and REM awakenings ($\chi 2 = (1, N_{paired} = 7) = 0$, $p = 1$) in absolute numbers. Cross indicates a trend in the group comparison ($p < 0.1$).

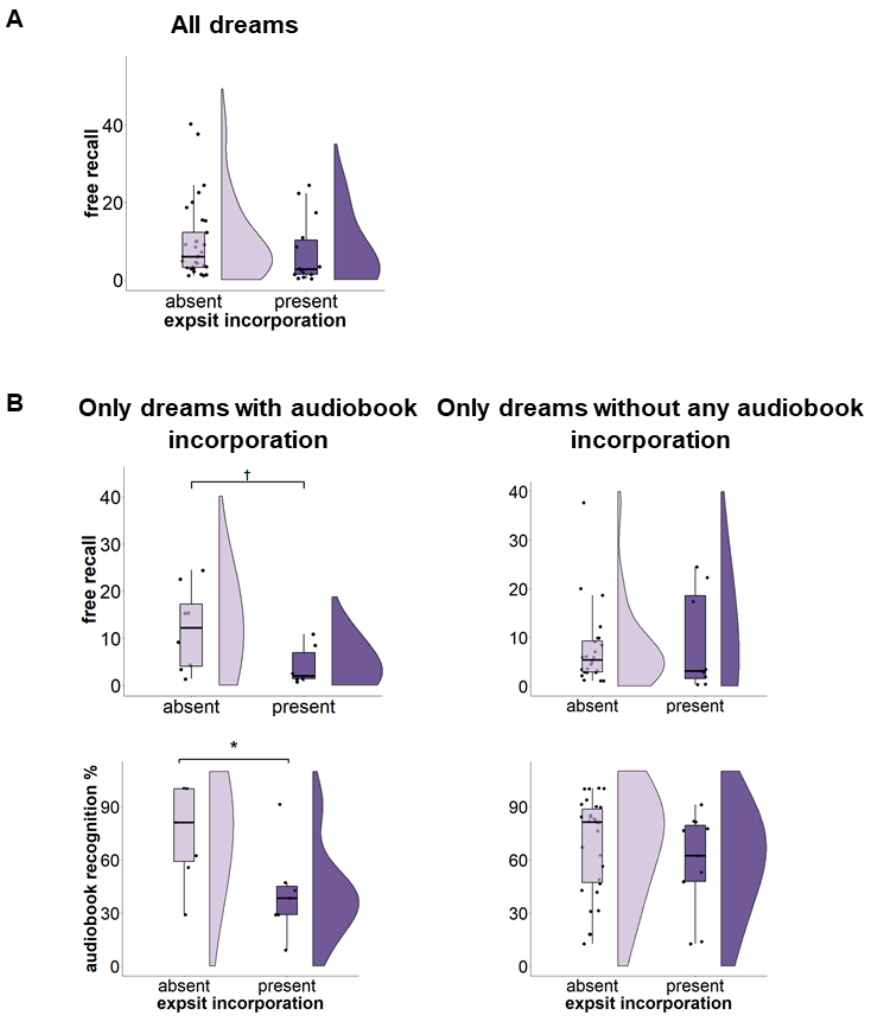


Figure S7. Memory performance in dreams with and without incorporation of the experimental situation.

A. Free recall performance comparison in dreams with and without incorporation of the experimental situation, whole dataset (U = 163.5, p = 0.1, CI [-5.75 0.58], N = 47, 1 outlier and 2 participants with missing data removed). The difference is not significant. **B.** Memory performance comparison between dreams where the incorporation of the experimental situation (*expsit*) is present or absent, in subsets of dreams with or without incorporation of the audiobook. **From top left to bottom right: (1)** Free recall performance, only dream reports including audiobook-related incorporations are pooled for this analysis (U = 9, p = 0.053, CI[-16.01 0], N = 14), the crossed T in the plot indicates a trend in the group comparison (p < 0.1); **(2)** Free recall performance, only dream reports not including any audiobook-related incorporation are pooled for this analysis (U = 84.5, p = 0.5, CI[-5.64 11.42], N = 33), the difference is not significant; **(3)** Audiobook-recognition performance, only dream report including audiobook-related incorporations are pooled for this analysis (U = 8, p = 0.03, CI[-0.71 -0.084], N = 14); **(4)** Audiobook-recognition performance, only dream reports not including any audiobook-related incorporation are pooled for this analysis (U = 118, p = 0.17, CI[-0.3 0.06], N = 41), the difference is not significant. In all the plots, the horizontal black lines within the boxplots represent the median value, whereas dots represent the single observations. Cross indicates a trend in the group comparison (p < 0.1), asterisk depicts a significant group difference * p<0.05).

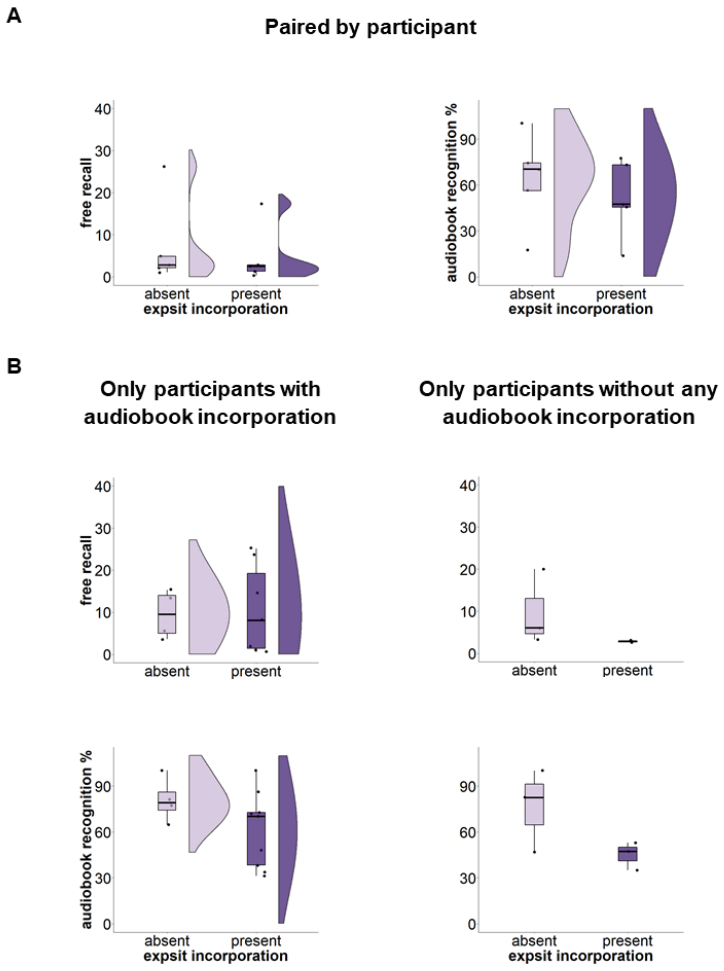


Figure S8. Memory performance comparison in participants with and without incorporation of the experimental situation.

A. Explorative reduced dataset including only observations that could be paired by participant. **Violin graph on the left:** Free recall (Z = 6, p = 0.7, CI [-0.49 0.16], N_{paired} = 5), the difference is not significant; **Violin graph on the right:** Audiobook recognition (Z = 4, p = 0.3, CI [-6.7 0.76], N_{paired} = 5), the difference is not significant. **B.** Memory performance comparison between where the incorporation of the experimental situation (*expsit*) is present or absent, divided by participants that reported at least one or no incorporation of the audiobook. **From top left to bottom right: (1)** Free recall, only participants for which at least one audiobook-related incorporation has been reported are pooled for this analysis (U = 13, p = 0.85, CI [-12.97 18.28], N = 11), the difference is not significant; **(2)** Free recall, only participants for which no audiobook-related incorporation has been reported are pooled for this analysis (U = 0, p = 0.08, CI[-17.46 -0.24], N = 5), due to the low sample size, data should be interpreted with caution; **(3)** Audiobook-recognition performance, only participants for which at least one audiobook-related incorporation has been reported are pooled for this analysis (U = 15, p= 0.4, CI[-0.43 0.22], N = 13), the difference is not significant; **(4)** Audiobook-recognition performance, only participants for which no audiobook-related incorporation has been reported are pooled for this analysis (U = 2, p = 0.28, CI[-0.65 0.06], N = 6), the difference is not significant, due to the low sample size, data should be interpreted with caution. In all the plots, the horizontal black lines within the boxplots represent the median value, dots represent the single observations.

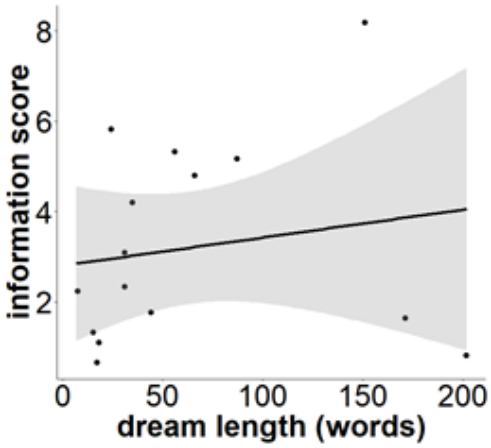


Figure S9. Relationship between dream length and audiobook incorporation.

Relationship between the amount of words in dream reports and the amount of information reprocessed in dreams ($\tau = 0.3$, $p = 0.14$ two-tailed, $N = 15$).

Table S1
Time spent in sleep stage by awakening

	Awakening 1	Awakening 2	Awakening 3	Awakening 4	Awakening 5
Time in S1 [mean ± SD]	8 ± 16 min	6 ± 4 min	14 ± 31 min	8 ± 7 min	4 ± 2 min
Time in S2 [mean ± SD]	18 ± 13 min	32 ± 17 min	44 ± 21 min	38 ± 23 min	13 ± 9 min
Time in SWS [mean ± SD]	28 ± 23 min	14 ± 14 min	10 ± 10 min	9 ± 13 min	10 ± 14 min
Time in REM [mean ± SD]	1 ± 3 min	11 ± 16 min	18 ± 16 min	25 ± 18 min	25 ± 24 min
Time awake during sleep [mean ± SD]	10 ± 17 min	5 ± 10 min	8 ± 10 min	7 ± 9 min	4 ± 4 min
Total time awake [mean ± SD]	23 ± 19 min	26 ± 27 min	22 ± 13 min	18 ± 12 min	9 ±8 min
Total time asleep [mean ± SD]	56 ± 62 min	64 ± 54 min	86 ± 79 min	80 ± 63	52 ± 48 min

Note. Based on sleep scoring data, 30-sec sleep epochs.

Table S2
Number of dreams and no dreams by awakening

	Awakening 1	Awakening 2	Awakening 3	Awakening 4	Awakening 5	All
Dreams	6	13	20	19	3	61
No dreams	14	8	4	5	1	32
Total	20	21	24	24	3	93

Table S3
Number of dreams and no dreams by participant

Participant	Dreams	No dreams
2	3	1
3	4	1
4	5	1
5	5	1
6	6	1
7	3	2
8	4	1
9	2	2
10	2	2
11	5	1
12	0	4
13	1	3
14	3	1
15	6	1
16	1	3
17	3	1
18	1	3
19	1	4
20	3	1
21	4	1
average	3.1	1.75
SD(±)	1.7	1.04

Table S4
Number of dreams and no dreams by last sleep stage prior to awakening

	S1	S2	SWS	REM	WAKE
dreams	5	32	3	11	10
no dreams	1	21	5	1	4
total	6	53	8	12	14

Table S5
Mean time spent in last sleep stage before reporting a dream

	S1	S2	SWS	REM	WAKE
Avg time (min)	6.40	8.72	12.17	24.55	15.60
SD(±)	7.8	8.69	12.97	18.15	11.25

Table S6
Distribution of last sleep stage by awakenings with dreams

	Awakening 1	Awakening 2	Awakening 3	Awakening 4	Awakening 5
S1	0	1	1	3	0
S2	4	9	14	5	0
SWS	1	0	1	1	0
REM	0	3	1	4	3
WAKE*	1	0	1	5	0

*In 6 instances out of 7, reports after wakefulness have been collected from late night awakenings, when participants already knew they would be asked for a dream upon multiple intervals, thus retaining their dream recall after spontaneously waking up before the planned awakening. These reports have been further evaluated to confirm that they resemble dream narratives and not waking thoughts or confabulations.

Table S7a
Influence of early vs late night on memory benefit, linear regression

Predictor	β (Estimate)	Std. β	t(8)	p-value	95% CI (Lower)	95% CI (Upper)
Intercept (early night)	0.60	-	2.71	0.03	0.09	1.12
Info score	0.07	0.07	1.13	0.29	-0.07	0.2
Night segment (late vs early night)	-0.47	-0.47	-1.86	0.1	-1.05	0.11
Info score x Night segment (late night)	0.02	0.02	0.3	0.78	-0.13	0.17

Summary:
$F(3, 8) = 6.53$, $p = 0.015$, $R^2 = 0.71$, Adjusted $R^2 = 0.60$

Table S7b
Influence of last sleep stage prior to awakening on memory benefit, linear regression

Predictor	β (Estimate)	Std. β	t(8)	p-value	95% CI (Lower)	95% CI (Upper)
Intercept (last sleep stage NREM)	0.08	-	0.53	0.61	-0.26	0.42
Info score	0.11	0.11	2.57	0.03	0.01	0.21
Last sleep stage (REM vs NREM)	0.63	-0.63	2.48	0.04	0.04	1.21
Info score x Last sleep stage segment (REM)	-0.09	-0.09	-1.57	0.15	-0.23	0.04

Summary:
$F(3, 8) = 5.02$, $p = 0.030$, $R^2 = 0.65$, Adjusted $R^2 = 0.52$

Table S8a
Indirect and direct audiobook incorporations in dream reports where all three raters agreed

	Original dream	**Translated dream**
Dream 1	*„Ich habe Seile gebunden, ich war alleine auf einem Segelschiff; dort waren noch Robben; das Segelschiff sah aus wie ein Spielzeug, ein altes, kleines Wikingerschiff; es gab auch Seerobben; ich habe eine Schnur geknotet; ich war zwischen Eis, in kaltem Gewässer, auf dem Eis waren Robben; ich habe versucht, loszukommen; ich habe Segel gesehen mit Seilen.“*	*“I tied ropes, I was alone on a sailing ship; there were also seals around; the sailing ship looked like a toy, an old, small Viking ship; there were also seals; I tied a rope; I was between ice, in cold water, there were seals on the ice; I tried to get away; I saw sails with ropes.”*
Dream 2	*„Jemand hat zu mir gesagt, dass ein Austausch nach Brasilien keinen Sinn macht, ich soll nur nach Portugal; ich habe geträumt, dass meine Versuchsleiterin es mir auf dem Iphone extra auf einer Karte gezeigt hat.“*	*“Someone said to me that an exchange to Brazil doesn't make sense, I should only go to Portugal; I dreamt that my experimenter showed it to me on the Iphone on a map, specifically.”*
Dream 3	*„Ich hab das Gefühl, vom Hörbuch geträumt zu haben, also dass das Hörbuch weiter ging. Irgendwie gings dann aber auch in TKKG über; also ich hab immer diese Elinor im Ohr, so wie die Tante heißt, und das ging jetzt über in TKKG wo Leute in der Nacht auch fliehen mussten und sich von Leuten verstecken, wo auch so bedrohliche Leute die verfolgt; auch so in ner dunklen Strasse; Leute, zwei Leute, wovon einer ein Junge und der ander ein Mädchen war und ich hab das ganze aus der Perspektive des Mädchens gesehen, das war aber nicht ich; die mussten glaub ich auch vor irgendjemanden wegrennen, die was von ihnen haben wollten und diese Leute waren sehr bedrohlich, z.B. das Mädchen und der Junge haben sich auf den Boden gelegt, um sich vor denen zu verstecken und dann kam irgendwie so ne alte Frau, die sich so runtergebeugt und böse: Hehehehe.“*	*“I have the feeling that I dreamt about the audiobook, that the audiobook went on, but somehow it also transformed into TKKG; I always have this Elinor in my ear, that was the aunt's name, and that transformed into TKKG where people also had to flee in the night and hide from people, where threatening people were chasing them; also in a dark street; people, two people, one of whom was a boy and the other a girl, and I saw the whole thing from the perspective of the girl, but that wasn't me; I think they also had to run away from someone who wanted something from them and these people were very threatening. For example, the girl and the boy lay down on the floor to hide from them and then somehow an old woman came and bent down and meanly laughs: Hehehehe.”*
Dream 4	*“Ich war in einem Flugzeug mit meinem Vater und der ist noch auf der Startbahn gefahren, dann hat er noch gemeint, ich muss jetzt losfliegen oder so etwas und dann ist er halt schneller gefahren aber irgendwie konnte er dann nicht abheben; dann hat er es ausrollen lassen; ich hab ihn noch gefragt: ja, du kannst doch gar nicht fliegen und dann hat er gemeint, mal schaun: und es war nachts und hat*	*“I was in an airplane with my father and he was still driving on the runway, then he said, I have to take off now or something and then he just drove faster but somehow he couldn't take off; then he let the plane roll out; I asked him: but, you can't actually fly and then he said, let's see: and it was at night and it was raining and there were people on the runway and they jumped away from him.”*

	geregnet und es waren Leute auf der Startbahn die sind dann weggesprungen vor ihm."	
Dream 5	*"Ich hab mich voll krass mit meinem Freund gestritten; wir sind völlig wild durch die Wohnung gerannt und haben uns angeschrien; dazu gabs nen Wasserschaden in der Wohnung; wo unten ein Haufen fremde Leute waren und irgendwie hat der [Freund] mich weggeschickt und ich musste das wieder machen; was bescheuert ist, weil ich sonst nie fremde Leute aus unserer Wohnung wegschicken muss; des war voll blöd."*	*"I had a huge fight with my boyfriend; we were running around the flat and yelling at each other; there was water damage in the flat; there were a bunch of strangers downstairs and somehow [the boyfriend] sent me away and I had to do it again; which is stupid because I never have to send strangers away from our flat; that really sucked."*
Dream 6	*"Durch den Kopf gegangen ist mir, irgendwas mit gestohlenen Diamanten und irgendwie, dass es auch eine Chip und Chap Folge gab in die Richtung."*	*"What went through my mind was something about stolen diamonds and somehow that there was also a Chip and Chap episode along those lines."*
Dream 7	*„Ich war in [Stadt], bei meinen Eltern; kurz zum Hintergrund; meine Eltern haben ein Haus und es gibt eine Wohnung nebenan, die sie gemietet haben, da ist eine Praxis drin, da muss man manchmal rüber gehen, um den Computer zu nutzen; das war Inhalt meines Traumes, dass ich da rüber muss in die anderen Bauten; ich musste mir die Schuhe anziehen und den Schlüssel holen, das habe ich gemacht; das Interessante war, dass ich in der Nähe vom Schlüsselbrett stehe und mir denke, okay, ich muss den Schlüssel haben und durch den Gedanken habe ich ihn quasi an mich herangezogen; dann war ich unten im Treppenhaus und hab die Schuhe gebraucht und die hab ich mir nicht einfach geholt sondern ich stand da mit offenen Händen und es war der Gedanke, dass die Schuhe zu mir kommen sollen und schon hatte ich sie in den Händen gehalten; ich hab mich angezogen, dann bin ich raus, das heißt ich war vor unserem Haus in [Stadt]; da war dann so ein Vorgarten und da war ein Hund, das hat mich halb überrascht, weil zum einen hatten wir früher einen Hund aber ich weiß, dass wir zur Zeit keinen Hund haben; dann kam dieser Hund auf mich zugerannt, das hatte erst den Eindruck, dass er sich freut und positiv gesinnt ist; nichtsdestotrotz hat er mich zu Boden gerissen quasi überwältigt, das hab ich auch gemerkt an der Perspektive, dass ich zu Boden ging und der Hund auf mich draufgesprungen ist;*	*"I was in [city], at my parents'; briefly for background; my parents have a house and there is a flat next door that they have rented, there is a practice in there, you sometimes have to go over there to use the computer; that was the content of my dream that I have to go over there to the other buildings; I had to put on my shoes and get the key, that's what I did; the interesting thing was that I stand near the key board and think to myself, okay, I have to get the key and the thought made me pull it towards me; then I was downstairs and needed the shoes and I didn't just get them but I stood there with open hands and the thought was that the shoes should come to me and I already had them in my hands; I got dressed, then I went out, that is, I was in front of our house in [city]; there was a front garden and there was a dog, that half surprised me, because for one thing we used to have a dog, but I know that we don't have a dog at the moment; then this dog came running towards me, at first I had the impression that it was happy and positively minded; Nevertheless, he pulled me down to the ground, overpowered me so to speak, I noticed that from the perspective that I went down and the dog jumped on top of me; and that scared me so much that I actually thought I had woken up, I had this room around me and actually the feeling that I was screaming, but that*

	und das hat mich so stark erschreckt, dass ich dann eigentlich dachte, aufgewacht zu sein, ich hatte dann diesen Raum um mich rum und eigentlich das Gefühl, dass ich schreien würde, dass aber nichts raus kommt, also nichts zu hören war; daraufhin hab ich angefangen mich zu wälzen, was wahrscheinlich nicht stimmt, das glaub ich nicht aber gefühlsmäßig wars so, dass ich mich hier rübergewandt habe, auf den Bauch gelegt, dann wieder hier rüber in die Richtung also relativ aktiv immer wieder mit dem Versuch zu schreien; und dann setzte etwas ein, das ich von anderen Träumen kenne, nämlich, dass sie an eine sehr reale Körperwahrnehmung gekoppelt sind; ab dem Moment hat es sich angefühlt, so wie jetzt die Körperwahrnehmung und ich hatte das Gefühl, dass ich fallen würde, das war nichts besonderes aber so wie in einem Aufzug, dieses Fallgefühl; das fühlte sich so an, als ob ich hier durch den Boden durchfallen würde; ich hatte ein vermeintliches Aufwachen im Traum und jetzt wirklich.“	*nothing was coming out, so I couldn't hear anything; I then started to roll over, which probably isn't true, I don't think so, but emotionally it was like this, I turned over here, lay on my stomach, then over here again in this direction, so relatively active, always trying to scream; and then something set in that I know from other dreams, namely that they are linked to a very real body perception; from that moment on it felt like the body perception now and I had the feeling that I was falling, it was nothing special but like in an elevator, this feeling of falling; it felt like I was falling through the floor here; I thought I was waking up in the dream and now I really woke up.”*

Table S8b
Indirect and direct audiobook incorporations in dream reports where all three raters agreed: references to the audiobook

	Incorporation (original)	**Incorporation (translated)**	**Time of related passage in the audiobook**	**Listened audiobook slot**
Dream 1	*"Humboldt befindet sich auf [einem] Segelschiff."*	*"Humboldt is on [a] sailing ship."*	00:49:46 - 00:53:21	00:43:00 - 00:53:00
Dream 2	*"Karte,in ferne Länder reisen. Südamerika, Portugal: ähnelt Reisestationen Humboldts."*	*"Map,travelling to faraway countries. South America, Portugal: Similar to Humboldt's travel stops."*	00:14:23; 00:46:45 -00:56:36; 01:25:18; 01:26:46; 01:36:31; 02:02:33 - 02:04:31; 02:13:43; 02:59:33 - 03:01:03;	00:00:00 - 2:00:00
Dream 3	*"Elinor (Explizit Name erwähnt), Bedrohung, Weglaufen, Mädchen."*	*"Elinor (explicit name mentioned), threat, running away, girl."*	00:19:09; 00:20:09 - 00:34:01; 00:56:55 - 01:10:25; 01:16:09 - 01:23:02; 01:39:55 - 01:49:36; 01:55:10 - 02:00:43; 02:03:47 - 02:08:32; 02:12:29 - 02:19:00;	1:17:00 - 2:19:00
Dream 4	*"Die Flucht, die Eile, Polizei und der bezug zum Vater."*	*"The escape, the haste, the police and the relationship with the father. "*	General theme of book (night, haste, flight, father)	00:29:00 - 1:02:00
Dream 5	*"Wasser, Springbrunnen ; Percy verursacht Wasserschaden (eigene Wohnung mit Elementen aus Percy vermischt)."*	*"Water, fountain; Percy causes water damage (own apartment mixed with elements from Percy). "*	General theme of the book (water)	1:06:00 - 1:25:00
Dream 6	*"Juwelen, Diamanten; Diamantendiebstahl (bzw. zu der Zeit angegebenen Zeit der Versuch des Diebstahls); Die Titelmusik von Chip und Chap hat im Text "Räuber, Diebe sind auf Ganoventour. "*	*"Jewels, diamonds; diamond theft (or at the time indicated, the attempted theft); The theme song of Chip 'n' Dale has the lyrics 'Robbers, thieves are on a crooks' tour."*	00:00:00 -00:12:39	00:25:00 – 00:56:00
Dream 7	*"Magie: Bewegung von Gegenständen durch Gedankenkraft, Angriff eines Hundes*	*"Magic: movement of objects through the power of thought, attacked by a dog."*	General theme of the book 01:55:15 - 01:57:36 (dog attack)	1:33:00 - 1:55:00

Table S9
Incorporation of the experimental situation

	Original dream	**Translated dream**
Absent	*"Ich hab geträumt, dass ich Geige spiele; und es lief die ganze Zeit von Chanson so ein Stück, das heißt Poeme."*	*„I dreamt that I was playing the violin; and all the time there was a song of chanson called Poeme playing."*
Present - implicit	*„Und dann war ich noch so an Dinger angeschlossen, was jetzt keine Überraschung war; die ganze Welt war an so Teile angeschlossen mit so Schläuchen und jeder hatte ein Nummer; da kam das glaub ich voll durch, was ihr gestern gesagt habt; dass das immer eine Nummer hat und man da so lang ziehen muss und jede Nummer kommt in einen Clip und bei mir hatte jetzt jeder auf der Welt ein so Ding und waren alle mit einem Mutter Kabel Ding verknüpft und haben alle unter der Erde im Dunkeln gelebt. Des war so ein düsterer Traum, wie so eine Kuppel unter der Erde und da waren exorbitant viele Menschen, also wahnsinnig viele Menschen und die hatten alle so ein Knüppelding am Kopf, aus dem ein Schlauch ganz weit nach oben ging; da war so eine riesige Röhre von der Kuppel irgendwo hin, keine Ahnung. Wir hatten auf jeden Fall so weiße Ganzkörperanzüge an."*	*"And then I was connected to things, which was no surprise; the whole world was connected to things with cables and each had a number; I think what you said yesterday surfaced; that it always has a number and you have to pull on it and each number belongs in a clip and in my dream, everyone in the world had such a thing and they were all connected to a mother cable thing and all lived underground in the dark. It was kind of a dark dream, like a dome under the earth and there were an exorbitant number of people, an insane number of people, and they all had a stick thing on their heads, from which a tube went quite far upwards; there was a huge tube from the dome somewhere, I don't know. We definitely had white full-body suits on."*
Present- explicit	*„Wir waren hier und es wurde eine Schlafstudie durchgeführt, eine Person war auf jeden Fall dabei, von dem ich weiß, wer es ist, der hat bei unserer eigenen Studie mitgemacht; der hat dann Testungen durchgeführt aber es lief alles schief der kam dann ständig und hat irgendwas gefragt; in dem Raum wo die Computer stehen, waren noch mehrere Leute da, du [Versuchsleiter*in 1] warst glaub ich auch da und die [Versuchsleiter*in 2] und jemand, den ich nicht kenne; das letzte war dann, dass diese Person aus meiner Studie reinkam und mit Tränengas gesprüht hat, er kam rein und es war lauter Nebel und er hat gefragt, wo irgendwas ist; er hatte mehrere Fragen gestellt, kam zwei bis drei mal."*	*"We were here and a sleep study was carried out, one person was definitely there, of whom I know who he is, he was part of our own study; he then carried out tests but everything went wrong, he kept coming and asking something; in the room where the computers are, there were several more people, I think you [experimenter 1] were there too and [experimenter 2] and someone I don't know; the last thing was that this person from my study came in and sprayed with tear gas, he came in and there was a lot of fog and he asked where something was; he had asked several questions, he came two or three times."*