Review article

Enhancing and advancing the understanding and study of dreaming and memory consolidation: Reflections, challenges, theoretical clarity, and methodological considerations

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A B S T R A C T

Empirical investigations that search for a link between dreaming and sleep-dependent memory consolidation have focused on testing for an association between dreaming of what was learned, and improved memory performance for learned material. Empirical support for this is mixed, perhaps owing to the inherent challenges presented by the nature of dreams, and methodological inconsistencies. The purpose of this paper is to address critically prevalent assumptions and practices, with the aim of clarifying and enhancing research on this topic, chiefly by providing a theoretical synthesis of existing models and evidence. Also, it recommends the method of Targeted Memory Reactivation (TMR) as a means for investigating if dream content can be linked to specific cued activations. Other recommendations to enhance research practice and enquiry on this subject are also provided, focusing on the HOW and WHY we search for memory sources in dreams, and what purpose (if any) they might serve.

1. Introduction

Memory is an essential cognitive capacity, which is ubiquitous in almost all aspects of human functioning. In order to be useful and applicable to future situations, acquired new information must pass through a consolidation process; consolidation thus forms a vital bridge between the stages of encoding and retrieval. While the exact biological mechanisms of the consolidation process are still debated, it is accepted that there are at least two recognised levels of consolidation that take place over differing temporal spans and at different neurological levels: cellular and systems consolidation (Born et al., 2006; Dudai, 2004; Dudai et al., 2015; Genzel & Wixted, 2017; Klinzing et al., 2019). Cellular, or synaptic, consolidation is a rapidly accomplished form of consolidation that takes place in the seconds and minutes after learning, where individual neurons may start firing together at encoding, forming the first footprint of a new memory trace. Systems consolidation involves connections forming between anatomical regions of the brain over much longer periods of time after learning, from days to weeks, maybe even years. As the present paper is concerned with how sleep and dreaming affect memory consolidation, systems consolidation is taken as the level of theoretical focus and the primary assumption, as cellular consolidation is likely accomplished before sleep begins, forming the first connections which will strengthen and evolve over further time in sleep.

The hippocampus and the neocortex are considered to be important parts of the brain in systems consolidation, as hippocampal-

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cortical connections form from the new memory traces that are born from neurons firing together at the cellular stage of consolidation. Over time, new memories undergo a neural reorganisation from a fragile, temporary mode of storage, vulnerable to interference, to a more permanent, stabilised form in the vast long-term memory networks of the brain, possibly without any further hippocampal dependence (e.g., Squire et al., 2015; Stickgold, 2005; Walker, 2008).

While most learning and retrieval of information takes place while we are awake and active and engaging with the world, the process of consolidation is arguably better suited to take place in the quiet night hours when we are asleep. While asleep, the amount of incoming new sensory information is drastically reduced, and there is more ample opportunity for the brain to process what was accumulated during wakefulness, sorting selectively through what is deemed most important and worth remembering for the individual's future; not all memories are consolidated equally, but some may be specially 'tagged' for consolidation because of their perceived future importance either at the point of encoding or retroactively (Cowan et al., 2021; Stickgold & Walker, 2013).

The role of sleep in memory consolidation has been much debated (e.g., Ellenbogen et al., 2006; Paller et al., 2021; Rasch & Born, 2013; Stickgold & Walker, 2005), but it is now believed that the reactivation and neural replay of learning-related brain activity during sleep is a strong candidate (but not the only one) for the mechanism actively responsible for consolidation (Ghandour & Inokuchi, 2022; Paller et al., 2020; Rasch & Born, 2008). This neuronal 'replay' activity in post-learning sleep has been observed at a very fine level in the hippocampal place cells of rats (e.g., Girardeau et al., 2017; Ji & Wilson, 2007; Lee & Wilson, 2002; Wilson & McNaughton, 1994), and similar types of activity have also been measured on less invasive levels in humans, in both sleep (e.g., Maquet et al., 2000; Peigneux et al., 2004; Zhang et al., 2017) and waking (e.g., Michelmann et al., 2016; 2018; Parish et al., 2021; Staudigl & Hanslmayr, 2019). The accumulated results of many studies have allowed for attempts at mapping the complex interaction between sleep stages (or physiological properties of sleep) and memory types (e.g., Diekelmann et al., 2009; Rasch & Born, 2013). Since memory is vital for our survival and coherent everyday functioning, memory consolidation, or alternative processes such as synaptic homeostasis, could well form one of the evolutionary payoffs of sleep, the ulterior compensation for being made to lie vulnerable and unproductive for hours each night, and a process that makes sleep, in the eloquent words of Matt Walker (2019), "*a biological necessity… your life support system, and mother nature's best effort yet at immortality.*" But one phenomenon that has remained conspicuously and almost consistently absent from the large majority of sleep and memory research is the phenomenon of dreaming.

Whilst the essential functions of sleep are now well-recognised, the sources, functions and purposes of dreams remain an enduring mystery. Some form of recognisable mentation or dream imagery — to varying degrees of frequency and quality — can occur across all the stages of human sleep every night (Nielsen, 2000; Schredl et al., 2013; Siclari et al., 2018; Zhang & Wamsley, 2019), from the transient, twilight-zones of sleep onset (Stenstrom et al., 2012) to the very deepest stages of slow-wave sleep (Cavallero et al., 1992). But many sleep and memory researchers do not sample dream reports from their participants during their experiments and studies, leaving what occurred on the conscious and subjective level of the mind during sleep unaccounted for and comparatively under-explored. However, interest is starting to grow regarding how dreaming, being so ubiquitous to the psychologically vital state of sleep, might contribute to memory processing and consolidation, or at least how memory reactivation and consolidation processes could explain the occurrence and qualities of dreams (see Fig. 1).

So far there is only indirect support for a relationship between dreaming and memory consolidation. Schredl (2017) groups the indirect evidence into three types.

1. *Correlation between brain activity and dream content.* A *meta*-analysis by Fox et al. (2013) identified distinct neural overlap in a network of separate but interacting brain regions, known collectively as the Default Mode Network (DMN),[1] across the stages of REM sleep and relaxed wakefulness, indicative of similarities with the state of waking mind-wandering. Furthermore, the same brain regions are involved when executing a particular motor action in dreams, in waking imagination, and for real when awake, producing very similar patterns of brain activity (Dresler et al., 2011; Erlacher & Schredl, 2008; Erlacher et al., 2003; Siclari et al., 2017). Evidence such as this, verified by dream reports, suggests that the brain neurologically executes dreamed and real behaviours and actions in much the same way, just as memories for past and imagined future events rely on comparable episodic simulation processes. The only difference is that motor output is blocked during sleep (especially during the body paralysis of REM sleep), preventing dreamed actions from being actually performed for real. In parasomnia cases where this paralysis fails to engage, individuals can sometimes be observed to enact behaviours, while still asleep, that are consistent with dream activities reported upon awakening (Oudiette et al., 2011). This dream-enacting behaviour could well be sometimes related to recent memories of events, worries and experiences, and may be an alternative way to study some dream content without the need for verbal reports, even in non-human animals (Malinowski et al., 2021). It seems that the neural circuits are still being exercised, possibly representing the reactivation of brain activity patterns that are related to a specific experience or learned skill — a neural simulation — that may contribute to further enhancement of ability or a memory.
2. *Continuity between waking life and dreaming.* The Continuity Hypothesis of dreaming states that dream content is not randomly and ambiguously determined, but is recognisably influenced by waking events, experiences and concerns (Domhoff, 2017a; Erdelyi, 2017; Schredl, 2003), to the point where it is sometimes possible to make quite accurate inferences about the waking life of the dreamer by reading only their dream reports (Bulkeley, 2012; Bulkeley & Domhoff, 2010). In light of recent reviews and debates

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[1] The DMN appears to become active when there is no effortful engagement with any particular task. In this taskless brain state, our thoughts turn inwards, reducing the attention we pay to our immediate surroundings, and this state is associated with spontaneous, stimulus-independent thought, which often circles around relevant self-concerns, drifting into reflecting on past experiences, fanciful imagination, and planning for future events and tasks that need to be done.
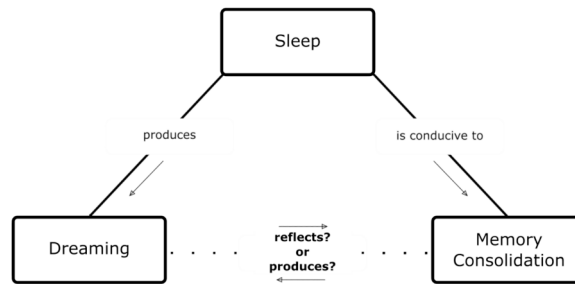
Fig. 1. A conceptual map of concepts and directions of enquiry. Sleep gives rise to dreaming, much in the same way that waking consciousness produces daydreaming and thought, and there is also plentiful evidence to suggest that sleep aids the consolidation of memories too. What remains uncertain is how dreaming and memory consolidation influence each other. Dreaming could be viewed as an unspoken mediator in the relationship between sleep and memory consolidation (i.e., memories are consolidated BECAUSE we dream of them), or, as is the view of this paper, memory consolidation processes could be a potential source of dreaming and dream content (i.e., we dream BECAUSE memories are being consolidated in sleep).

(Domhoff, 2017a; Erdelyi, 2017; Hobson & Schredl, 2011), it is important to distinguish cognitive continuity (enacting, embodiment and dramatizing of ongoing waking thoughts, concerns and conceptions) and experiential continuity (reflecting events or elements of events from prior waking life). Both may be evidenced in tandem in the well-documented example of when participants taking part in a laboratory-based sleep experiment dream about being in the laboratory itself during the stay (Dement et al., 1965; Hall, 1967; Picard-Deland et al., 2021; Schredl, 2008); experiential components include being in the laboratory environment, and interacting with the researchers and their equipment, while cognitive components include enactment of common participant concerns and worries, such as failing to fall asleep, unintentionally damaging equipment or sabotaging the experiment (which are plausible but may not actually occur for real). But just as waking memory and the remembering process are not perfect in accuracy, neither is continuity; very rarely do we dream of exact replications or re-enactments of singularly identifiable waking experiences (Fosse et al., 2003; Malinowski & Horton, 2014a). Instead, only fragments of waking life experiences may manifest in the dream, and the dream does more than just reflect them in their original form and content, as seen in the lab example mentioned above. Dreams may thus anticipate as well as reflect on waking life, drawing on similar past experiences and the imagination to aid prediction of what might happen, and sometimes resulting in completely novel, imaginary experiences and fantasies that may never happen in waking life (just as is possible in waking mind-wandering). Little specific function has been attributed to this continuity within the Continuity Hypothesis itself, but perhaps this could represent other forms of memory processing, such as creativity, extracting generalisations, integrating new information from recent waking experience, predicting how close future events might unfold, or even exploring creative, alternative possible scenarios that the waking mind may not initially conceive (Zadra & Stickgold, 2021).

3. *The effect of dreams on subsequent daytime behaviour and performance.* Since waking life has a noticeable effect on the content of dreams, some researchers have supposed that this dream content may have some reciprocal effect on subsequent waking life, in parallel to or as part of memory consolidation. Most empirical work on dreaming and memory consolidation has focussed on testing for an association between dream content that is continuous with recently acquired information or learned tasks, and subsequent improvement on that learned task. Findings, however, are mixed. Some studies have found positive support, that dreaming about a part of a learned task was associated with better recall or performance on at least one measurable component of that task (Fiss et al., 1977; Fogel et al., 2018; Klepel & Schredl, 2019; Plailly et al., 2019; Ribeiro et al., 2020; Schoch et al., 2019; Stenstrom, 2010; Wamsley et al., 2010b; Wamsley & Stickgold, 2019). Yet there are an equivalent number of studies which have failed to find such an association (Carr et al., 2023; Cipolli et al., 2001; 2004; Kussé et al., 2012; Solomonova et al., 2018; Stamm et al., 2014; Wamsley et al., 2010a; 2016), or too few dreams with task-related content were remembered to render such an analysis possible (Nefjodov et al., 2016; Nguyen et al., 2013; Ribeiro et al., 2021; Schredl & Erlacher, 2010). These studies are detailed in Table 1, and many of them were recently included in a very timely *meta*-analysis by Hudachek and Wamsley (2023), who found overall a strong and significant effect of task-related dream content for later memory performance, but only for dreams sampled from NREM stages of sleep. However this finding needs to be treated with caution, given the typically small number of participants in these studies (the average is 36), who are also typically young adults of student age (between 20–30 years old), and the heterogenous types of learning tasks used.

All three of these lines of evidence are important, and together they may help to explain the full picture of what is happening in the sleeping brain (on a neurological level) and mind (on a psychological level). The neural patterns of activity taking place during sleep, perhaps part of a memory reactivation process, could give rise to particular items of dream content, producing wake-dream continuity, and this continuous content may or may not have its own effects on the raw memory materials that compose it. Few though these studies (Table 1) are in comparison to the many on sleep and memory which have not sampled dream content, they appear to establish a standard for investigating for a relationship between dreaming and memory consolidation processes.

However, there is a missing piece of the puzzle, perhaps the most important piece of all: how do these memories make their way into dreams in the first place? By focussing on the functional associations of some waking experience being incorporated into dream

Table 1

An overview of research on memory consolidation and dreaming, including utilised tasks, incorporation rates of tasks into dreams (where reported), and effects of these dreams on subsequent memory (where reported).

Study	Task	Relevant aims, hypotheses and theoretical basis	Incorporation coding method	Analytical approach and awakening procedure	Sample and Incorporation rate	Outcome on post-sleep learning and dreams (where mentioned)
Carr, Wary, Grewal, Stafford, Raider & Pigeon (2023) [L, N,]	Learning the meanings of American Sign Language gestures	*"The primary aim of the current study was to assess the relationship between sign language learning and dreams collected from a morning nap, with the expectation that incorporation of task and laboratory elements in dreams would correlate with improved recall for signs following sleep."* (p. 236) *"While a recent meta-analysis supports that dream content is reliably associated with sleep-dependent memory consolidation (Wamsley, 2022), it remains unknown whether dreaming actively contributes to this memory consolidation. On the one hand, it may be that lab-related dreams simply reflect underlying consolidation of a participant's presleep experience. […] The causal interpretation would be that dreaming of the sleep lab actively enhanced sleep-dependent memory consolidation, perhaps as a sort of context-dependent memory enhancement during sleep. This is consistent with waking literature on context-dependent memory enhancement, sometimes known as the environmental reinstatement effect."* (p. 241)	Likert scales (1–9)	(1) Correlational: dream Likert scores against task improvement; (2) Nominal comparison: high incorporators (n = 8) vs. low incorporators (n = 5). Awakenings: Single awakening from REM sleep in a single 2-hour nap.	14 participants, mean age 21.31 (range 18–40), 9 female, 7 male (before exclusions – genders of the excluded participants not reported). Incorporation rate of ASL task: 11/14 participants (78.57 %); Incorporation rate of sleep lab: 13/14 participants (92.86 %).	Dreaming of the sign language task was unrelated to improved performance, but dreaming of the laboratory setting was associated with significant improvement. High lab incorporators improved significantly more than low lab incorporators, who significantly worsened after the nap.
Cipolli, Bolzani, Tuozzi & Fagioli (2001) [L, F]	Learning nonsense sentences	*"The cognitive concern thus induced was expected (i) to persist during the subsequent period of sleep, (ii) to guide processing and thus, (iii) to facilitate incorporation of the stimulus into dream experience. Incorporation, it was hypothesized, would be more frequent both in*	"Clark's associative rules": blind-coded semantic relation of dream content units to the words/content units of the sentence stimuli.	Correlational: frequency of incorporated words against proportion of content words retained. Awakenings: 3 awakenings from REM sleep in a single night.	12 participants, all male, age range 21–24. Incorporation rate of sentence stimuli: 26/36 REM dream reports (72.22 %) *	Recall accuracy of sentences did not improve as a result of dream incorporation

Table 1 (*continued*)

Study	Task	Relevant aims, hypotheses and theoretical basis	Incorporation coding method	Analytical approach and awakening procedure	Sample and Incorporation rate	Outcome on post-sleep learning and dreams (where mentioned)
		comparison with chance generation of similar contents in a control night, and in comparison with that of stimuli which had been the objects of previous recall tasks during the experimental night." (p. 278)				
Cipolli, Fagioli, Mazzetti & Tuozzi (2004) [L, F]	Learning nonsense sentences	*"Postulating that the processing of recent information during sleep improves consolidation both of the input (the pre-sleep stimulus) and output (the dream content), it follows that delayed recall ought to be better for processed stimuli than for unprocessed ones, and for contents of dreams which incorporate stimuli than for ones which do not."* (p. 318)	"Clark's associative rules": blind-coded semantic relation of dream content units to the words/content units of the sentence stimuli.	Retention rate of incorporated words vs. that of non-incorporated words. Awakenings: 3 awakenings from REM sleep in a single night.	12 participants, all male, age range 21–24. Incorporation rate of sentence stimuli: 31/35 REM dream reports (88.57 %).	Recall accuracy of sentences did not improve as a result of dream incorporation, but the dreams with incorporated features of sentences were better remembered in a morning retest
Dumel, Carr, Marquis, Blanchette-Carrière, Paquette & Nielsen (2015) [L, F]	Mirror Tracing	*"Some findings, in fact, support the general notion that dreaming plays a role in sleep-dependent memory enhancement (see reviews in Smith, 2010; Wamsley, 2014) […] While precise mechanisms of dream-related memory consolidation remain unknown, one observation with some empirical support is that task-related references incorporated into dream content are associated with consolidation (Smith, 2010; Wamsley et al., 2010). Individuals who recall frequent and detailed dreams may thus have more such references (indicating better consolidation), while individuals who have fewer and less detailed dreams may have fewer task-related references (indicating worse consolidation)."* (p. 373) *"…we expected to see correlations between MTT [mirror tracing task] performance and*	Number of task and laboratory elements incorporated into dreams (no specific details provided).	Correlational: emotions and features of lab elements against task improvement. Awakenings: Single dream report after 6.5 h of sleep in a single night. Stage of sleep on awakening not specified.	35 participants, mean age 24.7/24.9 (age range 18–35), 16 males, 18 females, 24/35 were students. Incorporation statistics not reported.	A link with dream recall ability: Infrequent dream recallers showed lowest baseline performance, but greatest overnight improvement (possible ceiling/ floor effects or regression to the mean). High dream recallers showed better task improvement associated with emotionally negative laboratory dreams.

Table 1 (*continued*)

Study	Task	Relevant aims, hypotheses and theoretical basis	Incorporation coding method	Analytical approach and awakening procedure	Sample and Incorporation rate	Outcome on post-sleep learning and dreams (where mentioned)
		REM sleep and between MTT improvement and the recall of laboratory dreams that are lengthy, remembered clearly and contain task incorporations." (p. 374)				
Fiss, Kremer & Litchman (1977) [L, F]	Recall of elements from a short story	*"It has been claimed with some justification [Hartmann, 1973] that REM sleep serves a memory-consolidating function, but the possibility that the experience of dreaming in and of Itself might serve a mnemonic function has not yet been explored. This study seeks to determine whether incorporating a pre-sleep experience into dream content will facilitate its later recall in the waking state. It is one of a series of ongoing studies testing the hypothesis that dreaming serves an adaptive function independent of its physiological correlates." (p. 122)*	Number of story elements dreamt about.	Correlational: number of story elements dreamt of against number of story elements recalled. Awakenings: Unspecified number of awakenings from every REM period that was longer than 10 min across two consecutive nights (extra info in Fiss, 1979).	6 participants, 3 male, 3 female, no further demographics reported. Incorporation statistics not reported.	Strong, statistically significant correlation of story recall accuracy with both number of story elements incorporated and number of dream episodes
Fogel, Ray, Sergeeva, De Koninck & Owen (2018) [L, N]	Virtual maze navigation and Nintendo Wii tennis	*"This reactivation and replay of newly acquired memories is reflected in the content of our dreams (Stickgold et al., 2000; Wamsley et al., 2010a, b; Kussé et al., 2012; Wamsley, 2014)." (p. 2)* "We predicted that: (1) the extent of memory consolidation will be related to dream incorporation, particularly for early dream reports, when learning-related dream incorporations are more direct…" (p. 3)	WordNet analysis of semantic similarity between dream, daydream and waking reports (% scores).	Comparisons of semantic similarity between wake and dream reports, plus a mediation analysis Awakenings: A minimum of 8 dream reports (+2 daydream reports) obtained from onset of NREM Stage 2 sleep in a 90-minute afternoon nap.	24 participants, mean age 23.3 (age range 20–35), 4 males, 20 females. 13–15 % similarity between dream and wake reports *(more precise rates not available)*	Incorporations in early NREM dream reports associated only with tennis improvement after a nap, not VR navigation
Klepel & Schredl (2019) [L, F]	Recall of details from a film clip	*"In the present study, dream incorporation effects on a memory task of watching a film sequence have been studied. Incorporators were expected to show better memory task results than non-*	Dreams coded for presence of items, people and actions seen in the film; film-dream similarity Likert scale (0–4).	(1) Comparison of dream content with age- and sex-matched controls and with adaptation night (t-tests) (2) Correlation: incorporated film content against film	22 students, mean age 23.09 (age range 20–28), 5 males, 17 females. Incorporation rate of film clip elements: 18/36 (50 %) of all REM and NREM reports combined *	Correlation between dream-film similarity scale and morning memory performance, but only when word count was controlled

Table 1 (*continued*)

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		incorporators." (p. 113)		detail recall change. Awakenings: Two awakenings on the experimental night: first REM period after mid-night viewing of film clip, and in the morning (7 from NREM, 8 from REM, successful dream recallers only).		
(Kumral, Palmieri, Gais & Schönauer, 2023) [L, F]	Recall of audiobook content	*"It has been proposed that the fragments of daytime episodes that resurface in dreams could reflect the neural reactivation of those experiences ([Klepel & Schredl, 2019; Siegel, 2001; Stickgold et al., 2001]). Whether the integration of memories into dreams depends on their neural reactivation and is thus instrumental to memory consolidation, however, remains elusive."* (p. 1) *"Although these findings have led to the proposal that memory reprocessing during dreams could support memory consolidation during sleep, the questions of how neural reactivation of learning content is associated with our dreaming experience and how this benefits memory consolidation, remain open."* (p. 1) *"We predicted that the narrative of the audiobooks should not only shape brain activity, but also the content of the dreams our participants experienced during sleep. [...] Crucially, if neural reactivation shapes the content of our dreams, we should observe a stronger neural processing signal in those participants who dreamt of the audiobook."* (p. 1) *"We explicitly chose this design to perform a hypothesis test for the question: is there any kind of information in*	Dreams coded for an overall incorporation score, based on how much information about the audiobook was detected in the dream (0–3), then multiplied by 1 or −1 depending on whether the correct audiobook was judged to match or not. Higher scores = greater evidence of direct incorporation.	Nominal comparison: high incorporators (average value above 0) vs. low incorporators (average value below 0). Correlational: free recall and recognition performance against EEG beta activity (judged to contain information about the heard audiobook). Awakenings Multiple awakenings (exact number not specified) across a single night approximately every 90 min.	20 participants, mean age 25.5 (age range 20–30, 10 males, 10 females. 32.9 % correct judgements for all dream reports (probability of identifying the correct audio book from a dream report) *	Blind raters could judge which audiobook a participant heard based on their dream reports with greater than average chance (REM dreams only). Beta power was judged to contain information about the audio books, and this significantly positively correlated with free recall and recognition performance on audiobook retention. No significant differences in recall or recognition of audio book content between high and low incorporators. *

Table 1 (*continued*)

Study	Task	Relevant aims, hypotheses and theoretical basis	Incorporation coding method	Analytical approach and awakening procedure	Sample and Incorporation rate	Outcome on post-sleep learning and dreams (where mentioned)
		the dream reports that pertains to prior learning, i.e., *information that allows raters to make correct judgements that exceed the number which would be expected by chance."* (personal correspondence) *				
Kussé, Bourdiec, Schrouff, Matarazzo & Maquet (2012) [L, N]	Playing Tetris for 6 h over 3 days	*"…it remains uncertain whether experience-related hypnagogic hallucinations reflect active memory processes or simply indicate the increased readiness to fire of neural populations whose synaptic connections were recently strengthened."* (p. 11) [study is largely exploratory and aims to replicate Stickgold et al., 2000]	Various categories of direct and indirect Tetris-related imagery	Correlational: gain in performance against rate of Tetris-related reports Awakenings: repeated awakenings at various intervals (15–180 s) after onset of NREM 1 sleep from a 90-minute daytime nap across three separate days.	43 participants in total, mean age (age range 18–33), 21 males, 22 females. Incorporation rate of Tetris task: 48/485 sleep onset reports (9.90 %) from 13/16 (81.25 %) participants in the Tetris group.	No relation between increase in game performance and rate of dream incorporation, except an association of 'maximum individual Tetris scores' with 'absolute number of Tetris-related sleep-onset reports'
Nefjodov, Winkler & Erlacher (2016) [L, F]	Wii Fit balancing board games	*"The purpose of this study is to examine the effect of a two-hour gross motor task training on dream content. The exploratory goal was to determine the consolidation effects of the dream content by comparing the performance of participants who dreamt of the experimental task to the performance of the participants who did not have task-related dreams."* (p. 89)	Dream reports scored for presence of lab references, game/balance activities, and console devices (YES/NO).	Nominal comparison between incorporators (n = 2) vs. non-incorporators (n = 9). Awakenings: 2–4 awakenings per participant from REM sleep across a single night.	13 sports students, mean age 26.8 (age range 23–33), 9 males, 4 females, Incorporation rate of balancing task: 2/36 REM dream reports (5.56 %) in 2/13 participants (15.39 %). Incorporation rate of the sleep lab: 17/36 REM dream reports (47.22 %) in 11/13 participants (84.62 %).	No significant changes in game performances, and no direct task-related dreams reported
Nguyen, Tucker, Stickgold & Wamsley (2013) [L, F]	Virtual maze navigation	*"Following our prior work, a secondary study goal was to examine whether dreaming of the learning task was related to memory performance."* (p. 1052)	Not reported.	*Analysis not attempted due to too few incorporations.* Awakenings: Up to 10 awakenings 30–90 s after sleep onset in the first hour of the night, 3 NREM-2 awakenings later in the night, one final report in the morning.	30 participants in total, mean age 19.6, 11 males, 19 females. Incorporation rate of maze task: 1/10 participants (10 %) in the sleep + awakenings group.	Relationship between dreaming and task improvement not possible to assess due to too few direct dream incorporations
Nielsen, Carr, Blanchette-Carrière, Marquis, Dumel, Solomonova, Julien, Picard-	Mirror Tracing, Corsi Block Tapping, Tower of Hanoi	*"Given the paucity of information about the effects of night awakenings and of recalling dream mentation on memory in humans, our protocol was designed to assess*	N/A (incorporations of tasks not explored).	ANOVAs including number of awakenings as a factor against nominal improvement on the task: (improved vs. not improved).	53 participants, mean age 24.2 (age range 18–35), 20 males, 33 females. *Incorporation statistics not reported*	A link with dream recall ability: participants with highest rates of dream recall (including bad dreams and nightmares) showed

Table 1 (*continued*)

Study	Task	Relevant aims, hypotheses and theoretical basis	Incorporation coding method	Analytical approach and awakening procedure	Sample and Incorporation rate	Outcome on post-sleep learning and dreams (where mentioned)
Deland & Paquette (2017) [L, F]		*whether these factors were associated with disruption or enhancement of REM sleep-dependent effects on performance for two tasks.*" (p. 89) *"Many have speculated that dreaming plays a role in offline memory consolidation (most recently* Smith, 2010; Wamsley & Stickgold, 2011*). This role is often sought by identifying experiential replays of task-related memories in dream content. However, such attempts have had limited success (*Smith & Hanke, 2004*).*" (p. 96)		Awakenings: single awakening from REM sleep in the morning after an uninterrupted single night.		the greatest improvement at Mirror Tracing
Plailly, Villalba, Vallat, Nicolas & Ruby (2019) [H, F]	Odour recognition and spatial association with pictures	*"A current hypothesis postulates that dream content reflects memory consolidation and predicts better post-sleep performance when a recent learning experience is incorporated into dreams.*" (p. 1) *"The first objective was to further test whether recalling a dream related to a recent experience is associated with improved memory performance, when memory encoding is not explicitly required and when odors are a part of the experience to be later recalled. […] Better memory performance in participants with learning-related dream reports were thus expected. The postulate underlying this prediction is that the more one reports dreams with elements of the task or of the context of the task, the more one dreams of the task.*" (p. 3)	Nominal: learning-related vs. not learning-related, based on resemblance to specific elements of the picture scenes. Two methods of scoring: 'strict' and 'liberal'.	Nominal comparison between incorporators (n = 16) vs. non-incorporators (n = 16) in strict scoring; incorporators (n = 21) vs. non-incorporators (n = 11) in liberal scoring. Awakenings: self-administered at home at 5am and again at usual waking time in the morning for 3 consecutive days. Sleep stages not recorded.	32 participants, mean age 21.94, 8 males, 24 females. Incorporation rate of task: 22/120 dream reports (18.33 %) in 16/32 participants (50 %) using strict scoring; 37/120 dream reports (30.83 %) in 21/32 participants (65.63 %) using liberal scoring.	Dreams with task-related and experiment-related content associated with better visuo-spatial memory when dreams were scored strictly, but not when dreams were scored liberally.
Ribeiro, Gounden & Quaglino (2020) [H, F]	Associative and relational memory for pictures of faces and objects	*"This study evaluated the effect of sleep in mediating episodic memory performances in a recognition task of visually associated elements. More*	(1) Nominal: determined by participant-reported impressions of whether the experimental situation influenced	(1) Nominal comparison between incorporators (n = 27) vs. non-incorporators (n = 36).	63 student participants, mean age 21.03, 9 males, 54 females. Incorporation rate of task items: 27/63 total participants	Participants who thought they had dreamed about the associations had better recognition performances of those associations

Table 1 (*continued*)

Study	Task	Relevant aims, hypotheses and theoretical basis	Incorporation coding method	Analytical approach and awakening procedure	Sample and Incorporation rate	Outcome on post-sleep learning and dreams (where mentioned)
		specifically, we examined how visually associated images create new relationships in memory during a learning process and the influence of these relations on subsequent recognition performance after a full night's sleep. In addition, we considered the influence of emotional salience of items on memory. Finally, we evaluated the effect of the incorporation of the studied material into dream mentation on memory performance." (p. 171) *"Our main expectation is to observe a quantitative benefit on memory performance for participants who slept after learning compared with those who remained awake. We also expected that participants indicating dreams about the study would have better memory performances on both relational and associative tasks."* (p. 174)	their dreams or not. (2) Item-based incorporation, based on retrospective recognition of associations in dreams.	(2) Nominal comparison between associations dreamt of vs. associations not dreamt of. Awakenings: natural awakenings at home across a three-day period (two full nights in total).	(42.86 %) wake and sleep groups combined; 18/31 (58.07 %) in the sleep group; 9/32 (28.13 %) in the wake group.	than those who did not, but overall performance did not differ between incorporators and non-incorporators.
Ribeiro, Gounden & Quaglino (2021) [H, F]	Associative and relational memory for items and locations in virtual reality	*"The main aim of this study is to evaluate how a full night sleep contributes to spatial memory performance for items displayed in a VR environment. We postulated that performance would be better at both the associative and relational levels after a sleep period than after a wake period. As a secondary aim, we sought to evaluate the likelihood of items from the task to be incorporated in dreams. We expect that associations implicating items incorporated will be more likely to be recalled than the others."* (p. 68)	Scored for presence of items seen by participants during learning (word search for direct correspondence in dream report)	Analysis not attempted due to too few incorporations. Awakenings: questionnaire in the morning after a single night slept at home.	57 participants in total, mean age 21.42 (age range 19–26), 13 males, 44 females. Incorporation rate of task items: 6/17 dream reports (35.29 %) from 6/27 sleep group participants (22.22 %); 6/11 participants who remembered a dream (54.54 %)	Too few incorporations for a proper analysis, but 5/6 items dreamt about were recalled correctly by the dreamer.
Schoch, Cordi, Schredl &	Picture-word associations	*"The major aim of the current study was to*	Scored for presence of categories that	Correlational: corrected	22 participants, mean age 23.32 (age	Significant positive correlation between

Table 1 (*continued*)

Study	Task	Relevant aims, hypotheses and theoretical basis	Incorporation coding method	Analytical approach and awakening procedure	Sample and Incorporation rate	Outcome on post-sleep learning and dreams (where mentioned)
Rasch (2019) [L, F]		*examine the effect of dream report collection during sleep on memory consolidation. Additionally, we examined whether a word-picture association learning task was incorporated into dreams and if this was related to memory performance the next day. We hypothesised that repeated dream collection will disturb ongoing memory consolidation. In addition, we expected incorporations in NREM and REM sleep, but that only NREM dream incorporation would be positively related to next day memory performance."* (p. 2) *"Our results support the notion that only NREM dreams might reflect ongoing memory processes, suggesting possible links between processes of memory reactivation/ consolidation and dreams during NREM sleep. One might speculate that incorporation of memories during REM sleep dreams might rather support some sort of emotional processing and re-evaluation. However, the relation between processes of memory consolidation and NREM* versus *REM sleep dreams clearly warrants further systematic examination."* (p. 7)	were depicted in the images, total incorporation scores produced (congruent and incongruent).	incorporation score against overnight memory retention. Awakenings: 3–6 per participant across a single night in the lab (up to 3 each from REM and NREM: 1 during early N2, 2 during N3, 3 5–15 min into REM). Totals: 50 from NREM, 56 from REM (nocturnal awakening group only).	range 19–35), 10 males, 12 females. Incorporation rate of materials: 91/128 REM and NREM reports (71.09 %) – nocturnal awakenings and undisturbed night groups combined *	the ratio of congruent and incongruent N2 dream incorporations and overnight memory retention
Schredl & Erlacher (2010) [L, F]	Mirror Tracing	*"Intense dreaming is an integral part of REM sleep (*Nielsen, 2000*), so the question arises whether memory consolidation processes that take place during REM sleep are accompanied by corresponding dreams. The continuity hypothesis of dreaming (*Schredl, 2003*)*	Nominal coding: dreaming of the task/ lab vs. not dreaming of the task/lab.	Correlational: dreaming variables against task improvement measures. Awakenings: 5–15 min into REM periods across a single night.	20 participants, mean age 22.7 (age range 19–29), 5 males, 15 females. Incorporation rate of task: 1/71 REM dream reports (1.41 %).	Not enough incorporations reported to conduct a full analysis, but dreams that were long, bizarre and negatively toned were associated with slower performance and lower error percentage, and REM sleep

Table 1 (*continued*)

Study	Task	Relevant aims, hypotheses and theoretical basis	Incorporation coding method	Analytical approach and awakening procedure	Sample and Incorporation rate	Outcome on post-sleep learning and dreams (where mentioned)
		stating that waking life is reflected in dreams is in favor of this idea. […] The present study was designed to investigate whether dream characteristics are related to the over-night improvement of a visuo-motor task (mirror tracing)." (p. 74)				significantly positively correlated with improvement in mirror tracing error percentage
Solomonova, Dubé, Samson-Richer, Blanchette-Carrière, Paquette & Nielsen (2018) [L, N]	Wii Fit balancing board game	*"To investigate the contributions of dreaming to sleep-dependent consolidation of a full-body procedural task, we assessed the dream content of a group of Vipassana meditation practitioners as an "expert" group in bodily awareness. the present article had two objectives: (a)…to test whether participants will dream about a procedural balance task learned before a nap and, if so, whether those dream incorporations predict improved performance on that task."* (p. 100–101) *"One of the proposed functions of dreaming is to facilitate offline memory consolidation. As dream content contains a seemingly unlimited variety of memory sources and is sensitive to waking life events, it may be that reactivation of memory traces in dreams is implicated in memory processing (Wamsley, 2014). Research that attempts to link dream content with memory and learning has so far produced mixed results (Schredl, 2017). There are two general approaches to viewing dream content in relation to memory consolidation: (a) dream content plays a role in memory consolidation in its own right, that is, independent of REM*	Total number of elements related to lab or balance task (direct = clearly traceable; indirect = resemblance to lab or task).	Correlational: task performance against incorporation incidence; Nominal comparison: incorporators (task and lab) (n = 20) vs. non-incorporators (n = 20). Awakenings: from N1 sleep and N2 (18 participants) and REM (18 participants) at the end of a single 90-minute nap.	42 participants, mean age 25.4 (age range 18–35), 21 males, 21 females. Incorporation rate of task: 3/12 (25 %) REM reports/ participants, 3/16 (18.75 %) N2 reports/ participants.	No relationship between task-related dreams and overall performance change, except for greater time spent in balance for control (non-meditators) group

Table 1 (*continued*)

Study	Task	Relevant aims, hypotheses and theoretical basis	Incorporation coding method	Analytical approach and awakening procedure	Sample and Incorporation rate	Outcome on post-sleep learning and dreams (where mentioned)
		sleep mechanisms; and (b) dreaming is an epiphenomenal correlate of REM sleep memory mechanisms." (p. 102) *"We expected [...] that their incorporation scores would correlate more positively with task improvement."* (p. 104)				
Stamm, Nguyen, Seicol, Fagan, Oh, Drumm, Lundt, Stickgold & Wamsley (2014) [L, F]	Virtual maze navigation with reward manipulation	"We hypothesized that by enhancing the salience of the navigation task, these features would "flag" spatial information with higher priority for sleep-dependent memory consolidation and incorporation into dream content." (p. 592) [no mention of whether dreaming of the task would be associated with improvement.]	Scored for presence of task content (direct = unambiguous representations; indirect = related sensations, persons, objects, locations, themes).	Nominal comparison: incorporators (n = 24) vs. non-incorporators (n = 31). Awakenings: up to 13 awakenings per participant across a single night (10 times within the first hour of sleep, one REM and one N2 report 30 min apart).	65 participants, mean age 21 (age range 18–30), 37 males, 28 females. Incorporation rate of maze task: 39/460 content reports (8.48 %) from 24/65 participants (36.92 %).	No significant relationships between improved performance and dream incorporation [This information reported in the supplemental content]
Stenstrom (2010) [L + H, F]	Episodic virtual environment exploration	*"We used the life-like events of our VR memory task to examine relationships between sleep-related consolidation of episodic memory and its incorporation in dreaming. [...] H4) Dreaming of the memory task will be associated with higher performance on the episodic task."* (p. 57–58) *"However, I hope to have made the case that the subjective experience of dreaming may have a causal role in memory processing, as opposed to the prevailing view which considers dreaming to be a consequence of memory processing (*Wamsley et al., 2010*), or to have no association with memory processing at all (*Diekelmann and Born, 2010*). Rather, the view espoused here is that dreaming is an elaborate orchestration of memory elements*	Likert scale rating by participants (1–9): *"To what extent was the virtual reality experience incorporated in your dream?"*	Nominal comparison: incorporators (n = 8) vs. non-incorporators (n = 8); Correlational: incorporation ratings against episodic memory measures. Awakenings: lab awakenings 5 or 20 min after onset of REM on the single lab night; natural awakenings using a home dream log for 9 days after the lab session.	16 participants, mean age 25.1, 3 males, 13 females. Incorporation of task on first night: 11/16 (68.75 %) participants. Incorporation of task on subsequent nights: 8/16 participants (50 %)	Task incorporation associated with better recall of spatial features of episodic memory, but overall incorporation ratings did not correlate with any measure of task performance.

Table 1 (*continued*)

Study	Task	Relevant aims, hypotheses and theoretical basis	Incorporation coding method	Analytical approach and awakening procedure	Sample and Incorporation rate	Outcome on post-sleep learning and dreams (where mentioned)
		into novel, plasticity-inducing perceptual experiences. The latter establish new relationships between objects, people, places and events that are different from those previously encountered during wakefulness." (p. 188)				
Stickgold, Malia, Maquire, Rodden berry & O'Connor (2000) [L, F]	Playing Tetris for 7 h over 3 days	[No clear statements of aims or hypotheses, but it appears to focus on the effect of playing Tetris on hypnagogic imagery in amnesic patients and normal controls.]	*"Only reports that explicitly described images or thoughts related to Tetris were counted."* (p. 351)	*Relation between task-related dreaming and later memory performance not tested.* Awakenings: a maximum of 10 awakenings per night, 15–180 s after sleep onset during the first hour of sleep across three successive nights.	27 participants in total: 12 novice players (age 18–25), 10 expert players (age 18–25), 5 amnesics (age 21–62, mean age 42.8). Incorporation of Tetris: 51/614 sleep onset reports (8.31 %) in 17/27 participants (63 %)	Low initial performance associated with increased rate of task-related hypnagogic imagery.
Wamsley & Stickgold (2019) [L, F]	Virtual maze navigation	*"This evidence raises the question of whether the activation of memory networks underlying dream content is related to sleep-dependent memory consolidation and to the effects of sleep on human memory. Importantly, this is not necessarily the case — the appearance of recent experience in dreams could be driven by neural processes entirely independent of those that support the consolidation of memory. However, we have previously reported that participants who dreamed about a virtual maze navigation task during a daytime nap showed a 10-fold greater performance gain at subsequent test than those whose dream reports were unrelated to the task, supporting this hypothesis (Wamsley, Tucker, Payne, Benavides, et al., 2010). This observation suggests that dreaming of recent experience reflects the reactivation and*	Nominal categories: direct incorporation, without direct incorporation.	Nominal comparison between incorporators (n = 8) vs. non-incorporators (n = 9). Awakenings: a maximum of 10 sleep-onset reports after 30–90 s of sleep, 3 awakenings from NREM stage 2 sleep, and one final report in the morning, across a single full night of sleep.	39 student participants, mean age 20, 13 males, 26 females. Incorporation rate of maze task: 39/310 (12.58 %) reports from sleep onset, N2, REM and resting wakefulness from 12/17 (70.59 %) of sleep group participants. 8/17 (47.06 %) sleepers reported related dream content.	Improvement in time to complete the task, with task-related dreams and wake reports predicting improvement

Table 1 (*continued*)

Study	Task	Relevant aims, hypotheses and theoretical basis	Incorporation coding method	Analytical approach and awakening procedure	Sample and Incorporation rate	Outcome on post-sleep learning and dreams (where mentioned)
		consolidation of memory in the sleeping brain, which in turn leads to post-sleep performance improvements." (p. 2)				
Wamsley, Hamilton, Graveline, Manceor & Parr (2016) [L, F]	Virtual maze navigation	*"The current study also examined the effect of "future relevance" on the incorporation of learning experiences into dream content. Our prior research established that memory consolidation during sleep is reflected in the conscious experience of dreaming. Research participants commonly dream of engaging, interactive laboratory learning tasks, and the extent to which recently learned information is incorporated into dreams predicts subsequent memory. We hypothesized that, if information with relevance to the future is selectively processed in the sleeping brain, dreams might similarly be influenced by the processing of recent memories with particular relevance to the future. […] we anticipated […] to find that information relevant to an individual's future also shows the highest rates of incorporation into dreaming."* (p. 2)	Same scoring methods as Wamsley et al. (2010b) and Nguyen et al. (2013): Direct relation or indirect relation to the task.	Nominal comparison between incorporators (n = 6) and non-incorporators (n = 45). Awakenings: a maximum of 10 sleep onset reports 30–90 s after sleep onset, 2 reports from later NREM2 sleep, 1 from later REM sleep, one final report upon awakening in the morning.	100 student participants in total, mean age 20 (age range 18–30, 40 males, 60 females. Incorporation rate of maze task: 7/370 (1.89 %) sleep onset, N2 and REM reports in 6/51 (11.77 %) sleep group participants	No significant relationships between overnight improvement and incorporation of task-related dream content, but expectation of retest significantly boosted performance in both wake and sleep conditions.
Wamsley, Perry, Djonlagic, Reaven & Stickgold (2010a) [H, F]	Playing Alpine Racer 2 skiing arcade game	*"The observation that memories are reactivated during sleep suggests that "replay" of memory in the sleeping brain could be accompanied, at least in humans, by related subjective experience (i. e., dreaming or sleep mentation)."* (p. 59) *"The present studies were designed primarily to examine the impact of learning on subsequent sleep mentation, rather than the effect of task-related mentation on next-day improvement."* (p. 65)	Content scoring: Direct incorporation = unambiguous representations of the game; indirect incorporation = related sensations, persons, objects, locations, themes).	Correlational: improvement score against presence of task-related mention. Awakenings: a maximum of 10 prompts per participant 15–300 s after NREM 1 sleep onset within the first hour of sleep, and a further reporting upon awakening in the morning. A similar procedure was also carried out in a separate group 2 h into sleep.	43 participants, age range 18–25, 16 males, 27 females. Incorporation rate of Alpine Racer content: 114/386 sleep onset and early NREM reports (29.53 %)	No significant relationship between improvement score and task-related reports

Table 1 (*continued*)

Study	Task	Relevant aims, hypotheses and theoretical basis	Incorporation coding method	Analytical approach and awakening procedure	Sample and Incorporation rate	Outcome on post-sleep learning and dreams (where mentioned)
Wamsley, Tucker, Payne, Benavides & Stickgold (2010b) [L, N]	Virtual maze navigation	*"It is now well established that post-learning sleep is beneficial for human memory performance. Meanwhile, human and animal studies have demonstrated that learning-related neural activity is re-expressed during post-training nonrapid eye movement (NREM) sleep. NREM sleep processes appear to be particularly beneficial for hippocampus-dependent forms of memory. These observations suggest that learning triggers the reactivation and reorganization of memory traces during sleep, a systems-level process that in turn enhances behavioral performance. Here, we hypothesized that dreaming about a learning experience during NREM sleep would be associated with improved performance on a hippocampus-dependent spatial memory task."* (p. 850) *"…it is not our contention that dream experiences cause memory consolidation during sleep. Instead, we propose that task-related dream experience and the subsequent behavioral enhancement of memory performance both result from an underlying process of memory reactivation and consolidation in sleep. Thus, dreaming may be a reflection of the brain processes supporting sleep-dependent memory processing."* (p. 853)	Open-ended verbal report, forced choice questionnaire (Yes/No). Incorporations counted as explicit and unambiguous mention of the maze task.	Nominal comparison between incorporators (n = 12) and non-incorporators (n = 10) in the sleep group. Awakenings: multiple awakenings across a single 90-minute afternoon nap – just prior to sleep onset, 1 min after sleep onset, and at the end of the nap.	99 student participants, age range 18–30, 44 males, 55 females. Incorporation rate of maze task (open-ended reporting): 4/ 50 nap group participants (8 %). Incorporation rate of maze task (forced choice question: 12/ 50 nap group participants (24 %).	Task-related dreams predicted improvement in completion time

[*] indicates that this information was not included in the original publication, and was obtained through calculation or personal communication with the authors.

[L] indicates that this study used a laboratory environment as the setting for dream reporting.

[H] indicates that this study used the participants' home environments as the setting for dream reporting.

[N] indicates that this study used naps as its sleep period.

[F] indicates that this study used a full night as its sleep period.

content, the mechanisms of dream production and memory incorporation have received much less attention in empirical dreaming and memory research. In order to understand what dreams do for memory consolidation (if anything at all), perhaps it first should to be understood what memory consolidation does for dreams (if anything at all), whether they arise from the same processes responsible for the consolidation of memories (i.e., memory reactivations in sleep). Once this has been established, it would provide a much stronger rationale for pursuing the additive benefits of dreams for memory, if they exist. This concern also aligns with a statement made by Smith and Little (2018, p. 2090), as they discussed issues regarding replication: *"...the style of research that remains most problematic for scientific psychology is research that is focused on demonstrating the existence of some phenomenon, as distinct from characterizing the processes and conditions that give rise to and control it."* The best research questions, they argue, are built from theoretical predictions, rather than aiming to demonstrate some phenomenon without consideration of the responsible process.

A crucial hypothesis set out by a number of detailed (but yet untested) theoretical models and writings (Horton & Malinowski, 2015; Murkar, 2013; Murkar et al., 2014; Paller & Voss, 2004; Payne & Nadel, 2004; Wamsley, 2014; Wamsley & Stickgold, 2010; 2011; Zhang, 2009) is that memory reactivations in sleep have two simultaneous effects: 1) they actively drive the process of memory consolidation, and 2) perhaps as a side-effect, they contribute to the production of dream content. This line of thinking (see Box 1) is indeed expressed, explicitly or implicitly, in some of the empirical papers in Table 1 (Fogel et al., 2018; Kumral et al., 2023; Schoch et al., 2019; Solomonova et al., 2018; Wamsley & Stickgold, 2019; Wamsley et al., 2010a; 2010b), but not consistently across all papers. More often, the expectations and hypotheses stated in these research papers are typically for an association between learning-related dream content and subsequent improvement on what was learned, citing mainly the studies which came before and reported the expected effect as justification for this expectation (see Table 1 for relevant quotations). The theoretical models say nothing of the effects of dreams on the memories they are made up of. Perhaps we should first ask: are these dreamed elements a result of memory reactivations in sleep? According to the models, it is these memory reactivations, which are part of the consolidation process, that are responsible for the improved recall. The dreams may be merely a by-product of this process, like the steam produced by a working machine; this steam may not have a function of its own, but it may be harnessed and put to other uses if you know how.

With reference to these models and their ideas, the aims of the present paper are to provide some critical and theoretical reflection and guidance on this area of research, its current state of progress, the assumptions and choices that may be made, and how it may be best to continue investigating. It aims also to provide some insight into *how* and *why* we look for a relationship between dreaming and memory consolidation in sleep. In short, what this field of research is perhaps most in need of is a simple pause to reflect and self-evaluate, to ask where we started, where we are now, how we got here, where we are trying to get to, and how and why we are trying to get there (Section 2.1). A call is made for methodological clarity and consistency, and a unified direction, grounded in a strong understanding of theory, when trying to determine how dreaming might be connected to memory consolidation in sleep. Empirical literature on this topic has already been reviewed by others (e.g., Hudachek & Wamsley, 2023; Picard-Deland et al., 2023a; Plailly et al., 2019; Schredl, 2017; Wamsley, 2014), focusing mainly on *what* was found, not so much on *how* it was found. The scope of this article is therefore predominantly conceptual, theoretical and methodological in nature, in a similar spirit to Domhoff's (2017a) article about the evolution and evaluation of the continuity hypothesis of dreaming. A similar overview seems to be absent from the field of dreaming and memory consolidation, a vital missing piece; we also need to be clear and consistent on *how* we investigate the question and carry out our experimental research, for there has been significant heterogeneity across studies in both methods and conceptualisations which may have complicated arriving at a clear, consistent conclusion. There are many choices that must be made at each step of the investigation process, and the consequences these choices can have on the outcomes need to be understood and evaluated (Section 2.2). This paper therefore also attempts to understand the overall findings of empirical work and reconcile it with a stronger theoretical foundation (Section 3), and proposes methods, a new way forwards, that may hold the key to testing the aforementioned models (Section 4).

2. WHY and HOW do we look for a relationship between dreaming and memory consolidation?

2.1. WHY: Understanding the default theoretical stance: The enhancement hypothesis (EH) of dreaming and memory consolidation

In searching for a relationship between dreaming and memory consolidation, authors of empirical studies on this topic (Table 1)

Box 1
Our logic and major assumptions about sleep, dreaming and memory reactivations, which are necessary to understand our views and reasonings within this paper.

1) Memories are consolidated in sleep by means of a neural reactivation process. (N.b., There are likely other processes at work too, but here we focus on memory reactivation).
2) Dreams frequently incorporate recognisable elements of recent waking thoughts, concerns and experiences (continuity).
3) If both preceding assumptions are true, then perhaps the continuity can be explained by those memory reactivation processes. Pursuing this enquiry, with verifying evidence of dream content manipulation using TMR procedures, offers an alternative means to show a relationship between dreaming and memory consolidation processes, beyond solely testing the effects of memory-related dream content on subsequent memory for what was learned.

most often state that they expect to find that dreaming of recently learned tasks or materials will be associated with improved behaviourally measured performance on that task or learning. But they are not always clear on exactly why they expect this finding, beyond reference to other studies which have come before, and which also arrived at that conclusion. Nevertheless, this seems to have become the default route of enquiry when attempting to understand how dreaming and memory consolidation might be linked, and a relevant hypothesis has been worded by Nielsen and Stenstrom (2005, p. 1289) as: *"dreaming about newly learned material enhances subsequent recall of that material."* This hypothesis, which might be implicit in the empirical research, especially if there is an assumed function to dreaming, will be referred to as the Enhancement Hypothesis (EH) from now on in this paper.[2] Whilst this hypothesis and expectation provides some unity in the form of a common objective, it seems to have rarely been questioned, and it therefore deserves some critical evaluation, especially in light of the mixed evidence that has so far been accumulated. Some pertinent questions are: Where did this idea come from? Who first established it and how? Is it an appropriate question to be asking? Does it still hold weight or does it need to be revised?

Although Nielsen and Stenstrom (2005) put it into clear words and identify it as 'the more widely recognised hypothesis' of how dreaming might be related to memory consolidation, they mention it only briefly and offer no insight into how it came to be the 'more widely recognised hypothesis'. Admittedly, this was not the aim of their article, but we were interested in attempting to trace its history and critically assess it. The earliest known reference to this idea within published scientific literature seems to date to the works of the Austrian-American researcher Harry Fiss in the 1970s, who wrote in the abstract of a brief study: *"This study seeks to determine whether incorporating a pre-sleep experience into dream content will facilitate its later recall in the waking state. It is one of a series of ongoing studies testing the hypothesis that dreaming serves an adaptive function independent of its physiological correlates."* (Fiss et al., 1977, p. 122). Whilst this is an important historical placemark, this source is very minimal on details, and does not clarify where this hypothesis came from or why this outcome was expected. However, some further details about this study are scattered across later book chapters that Harry Fiss authored (e.g., Fiss, 1979; Fiss, 1991), and these provide some rationalising. He cited work by Grieser et al. (1972) which found that REM sleep facilitates memory recall. With the known fact that REM sleep is also highly correlated with dream recall, it seems that Fiss took a further, logical, consequential step by asking if dreaming about a pre-sleep stimulus (during REM sleep) also facilitates its recall. It is therefore likely to be an independently drawn theory about the function of dreaming: if REM sleep consolidates memory, and dreams also take place in REM sleep, then maybe dreams contribute to memory consolidation too.

In that regard, it may be important to recognise the historical context of this idea. The 1970s saw something of a slump in dreams research compared to the more active 1950s and 1960s, with funding being directed elsewhere in science, although there were attempts to shift from the traditional psychoanalytic view of dreams to a cognitive one (Foulkes, 1996). The study of memory consolidation in sleep and dreaming can also be traced to the late 1960s and early 1970s, in searching for an adaptive function for REM sleep (Domhoff, 2017b), and this is likely to be a strong influence for the study by Fiss et al. (1977). By this time, other influential neurocognitive dreaming theories were starting to be developed and shared, chiefly the Activation-Synthesis theory published in the same year (Hobson & McCarley, 1977), and then inspired by this, Reverse Learning Theory a few years later (Crick & Mitchison, 1983). Activation-Synthesis proposed that dreams do not have a particular function, and are rather an incidental, synthetic, by-product interpretation of REM-based random neuronal firings happening deeper in the brain. On the other hand, Reverse Learning carries the view that REM dreaming is the sleeping brain's way of clearing out unwanted or unneeded information and memories, by reducing redundant neural connections. There was therefore still an interest in a function (or non-function) of (REM) dreaming, and Fiss et al. (1977) seemed to take the stance that dream content does indeed have a useful, memory-enhancing function. He was no doubt encouraged by his findings which appeared to support this; testing participants on recall for elements of a short story they read, he and his co-researchers found a strong, positive, and significant correlation between the number of story elements that were dreamt about and later recall of those story elements in a surprise retest.

However, strong though this correlation was, it cannot be concluded from this that dreaming of the story elements was what caused the greater recall of that story. Furthermore, this study is harmed by its brevity and the lack of methodological details reported in its published form; this publication seems to exist only as a single-page abstract, and the full depths of the findings are not explored. There were only six participants in this study, meaning that the power of the statistical analyses might be low, and it is not reported how ubiquitously in this small sample that story elements were dreamt about, or how frequently. The 'content checklisting procedure' used for identifying incorporations of the story task (and the stories themselves) are not provided for replication, which makes it difficult to understand and critique for its method (see Section 2.2 for further discussion on how we identify memory elements in dreams). Unfortunately, Fiss is no longer with us, the short 1977 abstract appears to be the only part of his "series of ongoing studies" to have been published, and it is not known if he ever carried out any more such studies.[3] Despite the very limited evidential value this study has, the idea behind it seems to have endured, but it was not until the new millennium when a new wave of studies began to pursue it again (see Table 1).

By this time, there was renewed interest in wake-dream continuity. The Continuity Hypothesis of dreaming can be traced to the 1950s in the work of Calvin Hall (1953), who initially treated it as a solely cognitive phenomenon, embodying in dreams the personal concerns and conceptions of the individual (Domhoff, 2017a; 2017b). By the 2000s, interest in continuity had broadened to include the

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[2] But we wish to stress, as highlighted by our reviewers, that few studies (see Table 1) ever cite this hypothesis directly. Most often they merely state to expect an association, not always with any indication of causal effects, and their results often remain only correlational.

[3] We have contacted the Centre for Jewish History in New York, which preserves a historical archive of the works, writings and letters of Harry Fiss, in an attempt to track down these other studies, but they replied that they have nothing apart from what has already been digitised on their website. It may be that these further studies were never conducted.

direct reflection of waking experiences in dreams, including day residues and dream lags (Schredl, 2003). Whilst there is plentiful evidence for the existence of wake-dream continuity, the Continuity Hypothesis is solely an observational hypothesis; no function or purpose has been firmly ascribed to it. The EH can provide a plausible extension to the Continuity Hypothesis by proposing such a function for it, parallel with the supposed psychological, memory-processing function of sleep, as Fiss (1991) elaborates. It can therefore be said to adopt the view that dreams are a meaningful, personally significant, and maybe even useful extension of waking thought patterns and processes (e.g., Graveline & Wamsley, 2015), and may serve some continuous function for the processing of information and material that is carried over from waking, into sleep and dreaming, and then again into subsequent waking. The EH can therefore be grouped with other theories of dreaming which endorse that dreams are inherently adaptive and functional for some important waking purpose, such as preparation of consciousness (Hobson, 2009), prospective or predictive coding, generalisation or optimisation (Hobson & Friston, 2012; Hoel, 2021; Llewellyn, 2016), or rehearsal of survival behaviours (Revonsuo, 2000).

However, it must be remembered that the true function of dreams is still unknown, and there is not enough evidence to confirm with confidence what function dreams may serve, if they indeed serve any function at all. Just because sleep may contribute to memory consolidation, that does not mean that dreams are automatically doing the same thing. Schredl (2017, p. 173–174) provides a similar caution, writing *"it is crucial to differentiate between physiological processes during sleep and the psychological level of dreaming. Although dreaming is related to activation of the sleeping brain it does not reflect the total brain activity during REM sleep or other sleep stages and, thus, the functions of dreaming must not parallel the functions of sleep in general and REM sleep in particular."* In other words, sleep and dreaming may have entirely separate functions. Furthermore, it is important to always remember and consider the null hypothesis, the possibility that dreams might have no actual function and were not selected for specially by evolution or something else (Blagrove, 2011; Domhoff, 2017b). This is important when considering how dreams are related to memory consolidation; the mechanistic components might be separate from the functional components, as succinctly worded by Blagrove et al. (2013) in the title of their paper: "Dreams may be made of memories, but not *for* memory.".

2.2. HOW: Methodological issues of testing the enhancement hypothesis

2.2.1. Falsifiability and power concerns

The EH (or searching for an association between task-related dreaming and improved task performance) can be challenging to test confidently, due in large part to the very nature of dreams. This may partially explain the diversity of results and difficulty in replications across studies reported so far.

To elaborate, it supposes that if the recently learned material is dreamt of, then there will be an enhancement in memory for it, and if it is not dreamt of, then there will be no such enhancement. However, it is one thing to say that someone did not *remember* dreaming about the target material, but that is not the same as saying they did not dream about it *at all*. Dream recall varies from person to person, and from night to night within individuals, dependent on a range of trait and state factors (e.g., Horton, 2023; Schredl et al., 2003). It is impossible to obtain a comprehensive sample of a single person's entire dream activity in a single period of sleep, otherwise sleep would be so fragmented and minimal as to abolish its effects and create further confounding conditions related to sleep deprivation. This is because the only way to gain any insight into the details of dream content is to awaken the sleeper and ask for a report[4]; with current technology, dream content cannot be monitored and recorded precisely as it happens like sleep can with polysomnography. As such, someone may have dreamt about the intended material at some point in the night, but forgotten it by the point of awakening and reporting, and then they would mistakenly be placed in the category of 'did not dream about the target stimulus'. This makes it extremely difficult (arguably, impossible) to confirm that someone *never* dreamt about the learning material at all, which raises issues with falsifiability. The EH, at least in the way defined by Nielsen and Stenstrom (2005) and Fiss et al. (1977), is not specific as to whether a dream needs to be remembered or not in order to have an enhancing effect, but the effects of unremembered dreams cannot be tested because their content cannot be accessed or verified that it even happened (Schredl, 2017; Schredl, 2021).

Notwithstanding the issues of dream recall, in order to test the EH, we are reliant on two variables or outcomes being met: 1) a statistically significant improvement in memory performance, and 2) a suitable amount of dream content that is related to the task. We have attempted to map and depict the combinations of these outcomes in Fig. 2: 1) dreaming of the learned content, and subsequently performing better; 2) dreaming of the learned content, but without subsequent performance improvement; 3) not dreaming of the learned content, but with a subsequently improved performance; and 4) neither dreaming of the learned content, nor a subsequently improved performance. From our observation, outcomes 1 and 2 allow the hypothesis to be confirmed or refuted more easily than outcomes 3 and 4, due to the confirmed presence of task-related dream content, but this needs to be tested in conjunction with outcome 4 in order to fully accept the EH, showing that dreaming of the learned task co-occurs with improved memory, and not dreaming of the task does not co-occur with improved memory. It may still be difficult to disentangle the memory effects of dreaming from the memory effects of sleep however. We do acknowledge that memory changes and dream content are not always simply dichotomous, but the prior research has often relied on such outcomes and groupings, and used these to structure their analyses and comparisons in between-groups designs, with correlational designs serving as an alternative (see Table 1, column 5).

Furthermore, in order to make a confident statistical conclusion, sufficient statistical power, mainly but not exclusively achieved through a large number of participants, measurement points or data observations is required; the greater the power, the more

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[4] However, future developments may offer alternative means of studying dream content and activity without the need for verbal reports, such as neural decoding of brain activity (Horikawa et al., 2013), or dream-enacting behaviour and neural replays/reactivations (see Malinowski et al., 2021).

confident we can be of discovering a true effect, if one exists (Baguley, 2004; Button et al., 2013; Sullivan & Feinn, 2012). Low or inadequate power remains a prevalent concern in psychological research (Abraham & Russell, 2008; Button et al., 2013; Crutzen & Peters, 2017; Vankov et al., 2014), and dreaming research is no exception; dreams are especially noisy in terms of their content and neural activity, so theoretically, a huge sample size would be required to overcome this noise and reduce the variability, and identify the presence of specific, learned content within a dream report.

However, studying dreams poses another obstacle, as identified above: while it is possible to obtain data on sleep and memory performance from all participants, it cannot be guaranteed that all participants who sleep will dream (or remember dreaming) about the learning material, or even recall a dream at all. This is important because of the recognised low rate of episodic event replay commonly identified in dreams (Fosse et al., 2003; Malinowski & Horton, 2014a), making incorporations of a particular material difficult to control, instigate or even identify clearly. The empirical studies (Table 1) show how difficult it is to make participants dream about intended content, often reporting incorporation rates that are around 10 % or less of all dream reports that were collected (Fogel et al., 2018; Kussé et al., 2012; Stickgold et al., 2000; Wamsley et al., 2010b; 2016; Wamsley & Stickgold, 2019), subject to coding criteria (see Section 2.2.2). In some cases there are too few to enable a statistically robust analysis (Nefjodov et al., 2016; Nguyen et al., 2013; Ribeiro et al., 2021; Schredl & Erlacher, 2010). The small number of cases of dreams with (valid) memory incorporations essentially become outliers in the overall data distribution, which is made up of a much larger number of dreams without clear incorporations. Therefore it may be very difficult to meet the required power[5] for such an analysis, and any effects of incorporations, being so typically few in number, would be lost in the averaging process of the comparative analyses frequently employed in these studies (although this would depend on exactly how incorporations are coded, see Section 2.2.2). Therefore, increasing the number of participants in a bid to increase statistical power is not guaranteed to provide the type of data that is most sought.

But perhaps the most crucial elements to be aware of are the assumptions underlying the identification of learned materials in dreams. When components of learned material do appear in dreams, this is not necessarily evidence of learning or memory consolidation (Domhoff, 2017b), because it has still not been evidenced that dreaming of learned material is indeed causal or complementary to memory consolidation or learning processes. Other uncontrolled or unmeasured factors, such as emotional involvement or personal engagement in the task, or even personal concerns related to task performance, could be responsible for this effect, as suggested in a series of studies by De Koninck et al., (1988) about dreaming of foreign language during an intensive French language learning course. Such alternative explanations may be more important determinants of certain dream content than the cognitive processes related to memory. In other words, the dreams do not serve as an environment for further learning to take place, but rather as an expression and exploration of the concerns surrounding the learning, a stance which is closer to the original cognitive form of continuity (Domhoff, 2017a; Hall, 1953), and similar to the propositions of the NExTUP theory of dreaming (Zadra & Stickgold, 2021).

Indeed, one suggested approach for future work is to explore relationships between general characteristics of dreams, such as emotional intensity, and memory consolidation, rather than between the presence of specific incorporations of the learned material as being indicative of a reactivation during sleep. This approach is more exploratory, open to different features of dreams, and reflective of the fact that dreams rarely replay prior experiences (Malinowski & Horton, 2014a).

2.2.2. ANALYSIS: Coding and comparing incorporations

Even when incorporations of a learning task do occur in a dream, further issues arise at the stage of analysis. Table 1 shows great variability not only in the choice of pre-sleep learning experiences used across studies, but also in methods of identifying and measuring incorporations in dream content, which affects the reliability and comparability of findings. Some measure incorporation as the number of to-be-remembered stimuli or specific task features that were judged to have appeared in the dream (e.g., Cipolli et al., 2004; Fiss et al., 1977; Schoch et al., 2019); others employ a nominal dichotomy of participants who dreamt of the task versus those who did not (e.g., Nefjodov et al., 2016; Plailly et al., 2019; Wamsley et al., 2010b); others still employ a more general Likert-scale rating of the degree of overall similarity between the dream and the task (e.g., Klepel & Schredl, 2019; Stenstrom, 2010). Even though all of these authors claim to be measuring the extent of incorporation (or continuity), their inconsistent methods of doing so highlight the absence of agreement on how to operationalise it, an ironic lack of continuity in the study of continuity (Schredl, 2012), and some methods may be more prone to measurement error. It would be beneficial to agree upon a consistent means, and also to agree on which of the chosen means are the most appropriate, and why. Different measurements have been sometimes shown to have different relationships with memory change. For example, Fiss et al. (1977) found a relationship between the number of story elements dreamt about and the number of same elements later recalled. Using different materials and a similar narrative task (recalling events and details from a short film clip), Klepel and Schredl (2019) did not find the same relationship, but instead found one between the overall similarity of a dream report to its learning material, and only when word count of reports was controlled.

On the subject of words, dream reports, being the only means to study dreams with current technology, have to be communicated by the dreamer and therefore analysed using the words they supply to describe their memory of their subjective experience; a second-generation rendition of the experience itself. Using these words to code incorporations also has the potential to lead to false positive incorporations, or conflations with unrelated dream content, especially for verbal learning material, if the proper care is not taken. This might have happened in the study by Cipolli et al. (2004), which reported some dubiously high incorporation rates of their nonsense

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[5] Statistical power is rarely considered explicitly in the empirical studies (Table 1). However the recent *meta*-analysis by Hudachek and Wamsley (2023) reports that a total of 25 participants in a between-subjects design would produce only a power value of 0.2 in detecting a medium effect size; in other words, an 80% probability of failing to find a true effect, if one exists. Therefore there is a dire need for ways to achieve greater power in this line of research.

Testing the EH		Was there a significant increase in recall for the learned material?	
		YES	NO
Was the learning task or material dreamt of?	YES	1	2
	NO	3	4

Fig. 2. An illustrative decision table for testing the Enhancement Hypothesis (EH). It presents four composite outcomes based on the two key questions relating to dream content related to the learned task occurring (in any form), and a quantitative memory improvement on the learned task. Participants could fall into any of these cells, but these cells need to be compared with each other in order to fully test the EH. When the answer to the dreaming question is NO, the EH becomes more difficult to answer conclusively, because it cannot be confirmed for certain that a participant definitely never dreamt about the task. In order to accept the EH, conditions 1 and 4 need to be observed: it needs to be shown that the people who did dream of the task improved their memory (YES-YES), whilst the people who did not dream of the task did not improve their memory (NO-NO), and these two conditions must be compared with one another.

sentence stimuli (88.57%, in 31/35 dream reports). Even though this was deemed significantly higher than their control conditions, and their inter-rater reliability was high (96.12 %) when scoring the dream reports, their dream content coding procedure was based on sometimes tenuous semantic associative relation to one or more content words from the sentence stimuli (e.g., a castle mentioned in a dream report was classed as a possible incorporation of the stimulus word 'bridge', with the link being castles might have draw-bridges). This could be an instance of the long-standing 'fixed effect' fallacy of language, of failing to treat linguistic stimuli as a source of random error variance (Clark, 1973; Malgady et al., 1979). A dream researcher has no control over the words a participant may choose to describe their dream experience, and this becomes yet another source of random error variance that few researchers may ever attempt to rectify or even recognise, on top of the random error variance already produced by the poor controllability of dream content. A similar problem may also occur with other memory stimuli too, particularly image stimuli; for example, if a to-be-remembered stimulus was an image of a dog, and a participant who viewed it subsequently dreamt of a dog, this may be classed as an incorporation by blind content-analysis. But further interrogation might reveal that the dog dreamed of was actually a real, identifiable dog that the dreamer themselves owns in waking life, and a totally different breed of dog than was depicted in the picture stimulus. With a little further probing, it may be learned that the participant may dream of their own dog quite frequently, therefore this type of dream content is not out of the ordinary for them, and likely holds different meaning than an image of an unrelated dog that features as a learning stimulus.

We use this example as a caution, to show that spurious incorporations may be identified, through conflations of incidental, un-related dream content with incorporations of the target stimulus, if a surface-level, blind content analysis is used. Established quantitative dream coding doctrine (e.g., Domhoff, 2000; Schredl, 2010) recommends that the coding be carried out by a researcher who is blind to any experimental conditions and manipulations, so as to reduce confirmation bias and other types of interpretative bias, while following a consistent, fixed set of coding instructions so as to be replicable by others. The dreamer themselves, being untrained in dream coding procedures, plays no part in this process. This is good and sensible advice, but it may be questioned if a 'blind' coder is always the most suitable person to be coding a dream which they themselves can never experience, and in total isolation from the waking life of the dreamer, which as the continuity hypothesis tells us, has a major influence on dream content. The day-residue and dream-lag literature has shown that many references to other events, concerns and preoccupations from waking life can frequently be identified in dreams (e.g., Blagrove et al., 2011a; 2011b; van Rijn et al., 2015), and the extent of this could well be a product of the analysis phase; some individuals may tend to search for and identify more or fewer incorporations in their own dreams than others, with more identifications diluting the day residue effect (Henley-Einion & Blagrove, 2014). These incorporations of other events need to be separated out from incorporations of the target task so as not to be confused unintentionally, and such biographical knowledge would not be known to the blind coders. In short, without biographical or contextual knowledge that only the dreamer could provide, false positives may be identified which have distorting implications on the conclusions of the research. It is encouraged that if blind coders do score dreams, their interpretations should be qualified with the dreamer themselves, who can provide very valuable insight and alternative (maybe more accurate) perspectives on the experiential qualities and meanings of many elements of their dreams in relation to their waking life (e.g., Bulkeley and Kahan, 2008; Edwards et al., 2015; Kahn et al., 2002; Malinowski & Pinto, 2021), averting potential misidentifications.

We must exercise diligence when trying to identify incorporations in dream reports, and not assume that any similar mention of something is a direct match to the to-be-remembered material. Fogel et al. (2018) offer a potential solution to this issue by gaining waking reports of the learning experience itself from participants as well as dream reports, and then comparing both reports for statistical semantic similarity. This could account for the unique, phenomenological, idiographic ways participants may make sense of their waking and dreaming experiences, and control for individual differences in language and vocabulary use. However, this may not work equally well for all tasks, and might be best suited for particularly episodic learning experiences, and may still be subject to specious incorporations based only on semantic similarity without exploring the deeper context.

Another new method used very recently by Kumral et al. (2023) aimed to manipulate pre-sleep learning using four different audiobooks, and then had blind raters judge which audiobook a participant listened to, based on information available in their dream reports (resorting to guessing if no information was present). This analytical concordance choice did not allow for a judgement of no incorporation at all, therefore there was deliberate noise in the judgements, and it resembles a machine-learning classification approach.[6] They concluded that on average there was enough information present in dream reports to allow the blind raters to make matches to the correct audio book significantly greater than chance levels, while accepting that this correct matching cannot be ascribed to either true information in the dream report or a correct guess. Nevertheless, it was concluded that memories can be reactivated identifiably in dreams, and this was further clarified with analysis of EEG beta activity which seemed to contain information relating to the audiobooks that were heard. This intriguing and novel method could help to determine whether memory reactivations are present in dream content above and beyond the noise produced by dream content in general, but needs to be replicated and confirmed with further development.

We also understand that consolidation could involve the integration of memories with existing networks and schemas as well as stabilising and strengthening the memory in its original form (Dudai et al., 2015; Gisquet-Verrier & Riccio, 2018; Wamsley & Stickgold, 2011). Therefore, incorporations in dreams (if related to this process) may not always be direct, especially if they occur in REM sleep, a stage of sleep which has been implicated in the integration and generalisation of memories rather than consolidation (e. g., Hartmann, 2010; Sterpenich et al., 2014). Indeed, many studies take into consideration 'indirect' incorporations of the learning material as well as direct ones (e.g., Kussé et al., 2012; Solomonova et al., 2018; Wamsley et al., 2010a; Wamsley & Stickgold, 2019), typically defined as dream content that bears an implicit resemblance to the learning material or activities. In light of this integration theory, the example of the dog mentioned previously could still be seen as a valid incorporation of meaningful information from the task. But this becomes problematic when the definitions and rules for exactly what constitutes an indirect incorporation can vary dramatically from study to study, and even between raters. Greater liberty in the scoring guidelines can produce quite different incorporation rates (e.g., Plailly et al., 2019), and inter-rater agreement can be very low when identifying indirect incorporations (e.g., Wamsley & Stickgold, 2019), raising concerns with subjective interpretation of dream content. Contextually relevant incorporations may be important however, as it was recently shown that dreaming of the sleep laboratory where learning took place was associated with better subsequent recall (Carr et al., 2023), seemingly similar to the classic context-dependent memory effect (Godden & Baddeley, 1975) playing out in sleep. This could therefore suggest an improvement in memory by virtue of association with the learning environment, but this needs further confirmation. Assessing the qualitative type of incorporation, from direct to indirect, with the latter reflecting possible metaphorical or non-obvious interpretations of continuity (see Malinowski, Fylan & Horton, 2014), as well as confidence in the score for each incorporation, could acknowledge this challenge and statistically control for it.

To summarise, the nature of dreams and the ways in which they reflect memories may not fit well with the methodological enquiries of the EH and other related enquires, and create difficulties in testing it confidently. This is exacerbated by some inconsistent and sometimes questionable methods by researchers when it comes to identifying memory correspondences in dream content. Analytical approaches are vulnerable to uncontrollable fluctuations in dream recall and language choice in reporting the dream. It may need some revising, or re-evaluating according to current evidence, but maybe a different question should become the default first. It would be better to first ascertain that dreams are indeed connected to memory consolidation processes in sleep, and there is more than one way to test this. The next section of this paper therefore presents a crucial missing piece of the literature on dreaming and memory consolidation: an overview, evaluation and narrative synthesis of existing theoretical models and core theory that treat dreaming as a complementary phenomenon to memory consolidation in sleep. It is recommended that this theoretical background serve as the starting point for all researchers who are interested in dreaming and memory consolidation in sleep.

3. A synthesis of theoretical writings and models on dreaming and memory consolidation

The models and theories covered here (Horton & Malinowski, 2015; Murkar, 2013; Murkar et al., 2014; Paller & Voss, 2004; Payne & Nadel, 2004; Wamsley, 2014; Wamsley & Stickgold, 2010; 2011; Zhang, 2009) all share the same key assumption and are therefore easy to group together or even combine into a single model. This key assumption is that the neural reactivation and replay of memories during sleep is responsible not just for the consolidation of these memories (which can be measured behaviourally post-sleep), but also a source of dream content as well, producing the commonly observed patterns of wake-dream continuity. In other words, dreaming is treated as evidence of memory fragment replays and reactivations taking place in the sleeping brain, while at the same time being experienced and elaborated at a conscious and subjective level. Picard-Deland et al., (2023a) recently reviewed the current knowledge and evidence to support and refute this idea, but the following is a narrative synthesis of the theoretical models, which can also help guide future empirical investigations and aid understanding.

These models are based largely on documented overlaps between the sleep stages associated with the consolidation of memory types according to the dual-process hypothesis and the typical characteristics of the dreams that are sampled from those sleep stages. This view can be traced to some theoretical papers published in the early 21st Century (e.g., Baylor & Cavallero, 2001; Nielsen & Stenstrom, 2005; Paller & Voss, 2004; Schwartz, 2003; Stickgold et al., 2001), which concerned how dreams may align with sleep-based memory processes based on how they are influenced by waking life. Broadly, NREM-sleep is associated with declarative memory consolidation and NREM dreams are accordingly more episodically sourced, while REM sleep is associated with more complex

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[6] We acknowledge and thank the authors of this paper for their personal correspondence, and helping to explain the nuances of this procedure to us.

and emotional memory processing and REM dreams are correspondingly more emotional, bizarre, and contain more abstract and semantic memory sources, possibly intricate combinations of many (Murkar, 2013; Payne, 2010; Wamsley & Stickgold, 2011). As a result, dreams are taken as a conscious manifestation of portions of declarative memory, sourced from cross-cortical traces, being accessed, reactivated and processed during sleep, rather than entire episodic events (Horton & Malinowski, 2015).

Different brain activation patterns are believed to be responsible for this difference between NREM and REM dream phenomenology and content (Murkar, 2013), with particular importance ascribed to levels of neurotransmitters, particularly the stress hormone cortisol (Payne, 2010; Payne & Nadel, 2004). In their model, Payne & Nadel (2004) draw on evidence that naturally varying levels of cortisol across the night can alter the status of hippocampal-neocortical circuits, the two core brain regions involved in systems-level declarative memory consolidation (Nadel et al., 2007), and this has an impact on memory processes. When cortisol levels are low in NREM sleep, particularly SWS, hippocampal-neocortical communication can occur, and therefore episodic memories that appear in NREM sleep in the earlier half of the night are likely to be more intact and accurate to reality. This is supported by some studies which show that the most direct incorporations of a given experience tend to appear in early-night NREM sleep or near sleep onset (Fogel et al., 2018; Stenstrom et al., 2012; Stickgold et al., 2000; Wamsley et al., 2010a). In REM sleep, when cortisol levels are higher, hippocampal-neocortical communication is altered, possibly even reversed, and new connections are made therefore between separate but similar concepts and experiences within the neocortex itself, and only fragments of episodic memories, isolated from their original context, are activated. The sleeping brain, just as it does when presented with fragmented information while awake, automatically looks for patterns and meanings therein, attempting to synthesise the fragments into narrative themes, and in REM, this will produce the complex and bizarre dream narratives that are often reported, perhaps as a result of hyperassociation (Horton & Malinowski, 2015). In other words, the type of mental experience a person can have is dependent on the brain activity, and the parts of the brain which are available and active, during that certain point in sleep (Horton, 2023). This may be tested with measurements of cortisol strength across sleep stages, memory consolidation extent, and the episodic accuracy of dream content.

The proposed function of this memory process (specifically, a *declarative* memory process) is to assemble together the recent experiences of an individual's life along with their ongoing goals, desires and problems, for the adaptive purpose of tuning behavioural strategies and reorganisation of memories that are related to ongoing emotional issues (Paller & Voss, 2004). All information involved is therefore relevant and useful for subsequent waking experiences, according to this idea. The resulting dream content may be a tangential narrative that is produced to connect the different memory fragments, smoothing them all together. The ultimate goal being achieved is the forming of new connections between and among newer and older memories, central for both consolidation and problem solving, and expanding the relevance and meaningfulness of individual memory fragments.

It might be an overstatement, however, to say that all dream content is inherently meaningful or applicable to waking-life goals and problems. The hyperassociative connections that form between isolated memory fragments may result in bizarre, unrealistic dream content (Horton & Malinowski, 2015; Payne & Nadel, 2004), including actions and solutions which are non-sensical or impossible to achieve within the constraints of waking life. For example, one may dream about being attacked by a violent offender on the streets (a terrible event, but possible in waking life), but may then subsequently escape the danger by leaping into the air and flying out of reach (which is impossible in waking life). In such cases, the connections formed and manifested in dreams in this way may be exploratory or incidental, wandering into the realms of fanciful and vivid imagination, with no actual adaptive purpose or function. It is therefore not appropriate, writes Wamsley (2014), to expect every component of every dream to bear relevance to memory processes and learning experiences, or even to be applicably helpful in any way to real-life problems. Not all dreams may evidence forms of memory consolidation; memory consolidation is but one of the proposed underlying possible formations of dreams, and given the documented examples of discontinuity in dreams (Hobson & Schredl, 2011; Horton, 2017), it seems reasonable to expect dreams not to replay whole memories perfectly. Again, human memory itself is not perfect; not every single detail of every single waking experience will be encoded or consolidated beyond short-term memory, and the dreaming brain may fill in the gaps with imaginative possibilities or pieces of other memories that may fit. We must therefore take care when we follow the assumption that memory for dreamt events is inherently inferior to memory of waking events (Chapman & Underwood, 2000; Horton, 2011a; 2011b).

The inaccurate, non-veridical replay of memory events in dreams was an early contention to the idea that sleep and dreaming are involved in memory processes (Vertes, 2004). But an important theoretical component of the consolidation process is not just to preserve memories in their original form, but also to transform them, maybe even isolate their component parts so that they may be integrated into existing memory networks in the brain (Dudai et al., 2015; Wamsley & Stickgold, 2011). In this way, memories may be taken apart, analysed, trimmed and sorted with regard to their components, and new connections may form with existing memories stored in neural networks of the brain, filling the gaps between individual memory components with newly associated information drawn from other past memories. This may materialise as the dream content; sleep is probably doing more than just strengthening and consolidating memories, but may also contribute to creative thinking, future planning, memory updating and optimising (Ghandour & Inokuchi, 2022; Jha & Jha, 2020), a process which might also be shared with dreams (Hobson & Friston, 2012). This may then explain why fragments pertaining to particular experiences from throughout the lifetime (e.g., Malinowski & Horton, 2011; Stenstrom et al., 2012) may often appear alongside each other in dreams, interleaved by some shared semantic property that the sleeping brain is in the process of identifying and integrating, perhaps tying together semantic knowledge and episodic experience in an exploratory or hyperassociative way, thus creating new connections rather than replaying existing ones wholly (Hartmann, 2010; Horton & Malinowski, 2015; Zadra & Stickgold, 2021). Also, it is unfeasible to assume that just one single type of memory (e.g., declarative, procedural, episodic) is being reactivated at any one time; just as in waking experience, multiple memory types may co-occur, working in tandem to make cognitive life possible, and thus multiple memory systems are also likely to be involved in sleep-based reactivation (Payne & Nadel, 2004; Schwartz, 2003). This non-veridical re-experiencing of the original memory parallels the statistically similar but non-exact reactivation of neural activity, which occurs in a more accelerated fashion than in waking, at least as is observed in studies

on rats (Euston et al., 2007; Lee & Wilson, 2002).

Horton and Malinowski (2015) describe a model which suggests that dreams more likely reflect the consolidation of autobiographical memory. Similar to Payne and Nadel's (2004) model, and the earlier writings of Hartmann (2010) concerning the connectivity of memory fragments in dreams, this involves the engagement of the entire declarative memory system, as both episodic and semantic memory are processed in tandem, drawing on the close relation of both to facilitate the encoding of a memory or experience as accurately as possible. Autobiographical memory contains both semantic and episodic components, forming a personal kind of life story, which evolves dynamically over time with regard to the new information and life events constantly affecting the self (Conway, 2001). Memories can be broken down into their declarative elements or details, which can be reactivated in NREM sleep stages freed of their original context. These elements may then be combined and recombined in novel, hyper-associative ways during REM sleep, similar to the ideas of Paller and Voss (2004) and Payne and Nadel (2004), as their salient components are efficiently integrated into existing knowledge networks, plausibly explaining the stereotypically heightened bizarreness often reported in REM dreams.

This notion of hyper-associativity is comparable to the NEXTUP model of dreaming (Network EXploration To Understand Possibilities) by Zadra and Stickgold (2021), which ascribes a function to the dreams produced in this way. Based on much of the information that inspired the previous models, the NEXTUP model proposes that the evolutionary function of dreams is not to strengthen the memory material that comprises the dream, but to explore novel connections between weakly associated memories, and allow the dreamer to understand possible scenarios and their reactions to them. In this way, potentially useful, creative and insightful new ideas may emerge from dream-simulated 'what-if?' scenarios, helping the brain to calculate which associations are of potential future use. This happens across all the sleep stages, beginning with the hypnagogic imagery experienced at sleep onset, which is usually closely tied to pre-sleep concerns and thoughts. This 'tags' memories requiring further attention deeper into sleep, progressing first to N2 where other recent, strongly associated memories are identified, explaining the more episodically sourced memory content of N2 dreams. Then in REM, the brain searches for more remote, weakly associated memories, and generalising from them to better understand their integrated meaning. Dreaming thus serves a function that is separate from the neural memory reactivations which drive them. This is an intriguing idea, but it needs verifying with empirical data.

However, again, the proposals of these models may be over-generalised or built upon over-generalisations. For example, the electrophysiological properties that are common across some sleep stages (e.g., spindles, slow oscillations, power in certain frequency bands) bear a stronger relation to memory processes than the more broadly-defined sleep stages (e.g., Ackermann & Rasch, 2014; Diekelmann et al., 2009; Fogel & Smith, 2011; Genzel et al., 2014; Stickgold, 2013; Wei et al., 2018). It may not always be appropriate therefore to ascribe the global sleep stages as being responsible for the consolidation of a particular type of memory. For example, just because there are far fewer slow waves or spindles occurring in REM sleep, this does not necessarily entail that consolidation linked to these micro-features of sleep cannot happen in REM. We report more on this in Section 4.

Further, the content of dream reports is highly dependent on ability to recall and articulate details (many of which may not be remembered), or the temporal duration of a dream, a difficult aspect to measure accurately and directly. Many participants in dream studies are not well-trained in self-observation and identifying memory sources of their dreams objectively, or they may unwittingly modify or censor their dreams for improved narrative comprehensibility, or omit details they are uncomfortable with sharing (another potential source of random error variance and contributor to lost data – see Section 2.2.2). Thus, the recalling process may add more to the dream report than was actually present in the dream. Also, the qualitative differences of REM and NREM dream reports are not always distinguishable (Monroe et al., 1965), and tend to disappear when the length of dream reports is controlled (Casagrande et al., 1996; Cavallero et al., 1990), meaning that the differences could be a product of the reports or reporting process, or how experienced an individual is at recalling dreams and other episodic memories, not the dream experience itself. Furthermore, not all REM dreams are inherently or uniquely bizarre (Colace, 2003; Domhoff, 2007), which casts doubts on the neurobiological conditions and hyper-associative processes of REM sleep being the source of that bizarreness.

Finally, the qualities of dreams from these sleep stages may change across the course of the night, such that late-night dreams, be they from REM or NREM sleep, are more 'dreamlike' than their early-night counterparts (Carr & Solomonova, 2019; Pivik & Foulkes, 1968), and wake-dream continuity becomes more integrated in late-night dreams (Malinowski & Horton, 2014b; 2021). Dream memory sources seem more hyperassociated, with individual sources coming from temporally distinct periods of life, as a function of time spent asleep. Whilst this may reflect characteristics of dream recall from REM, it could also reflect retrieval abilities being more sophisticated as the dreamer approaches wakefulness, or increased dream source integration or complexity as a result of having been processed over numerous iterations of sleep cycles. However, with serial awakenings across the night, such time-of-night effects may be diluted or disrupted by the repeated interruption of sleep (Martin et al., 2020), and any effects of time of night ideally need to be differentiated from sleep stage, and time spent asleep.

To take the main points of all of these models together with the evidence they are based on, they suggest that the dream content one experiences is a natural by-product of the neurophysiological brain processes underlying memory consolidation in sleep, subjectively reflecting semantic and episodic information from waking life, extracted from their original context, being consolidated into a more stable form. This information is reactivated in sleep, and neurotransmitter variations across the sleep stages, particularly cortisol, determine the ease of communication in hippocampal-cortical circuits, which influences the mechanics of memory processing. This then in turn determines the phenomenology of dreams, and what is capable of being experienced based on the capabilities of the brain in that particular state of sleep. Novel links are formed (perhaps hyperassociatively) with other existing memory fragments already in storage. In the transition from sleep to waking, as waking consciousness starts to re-establish itself, the memory consolidation is perceived and experienced as dream recall, which is then submitted as a written report of subjective experience.

Crucially, nothing is proposed in these models about the possible functions that these produced dreams may then have for subsequent memory, such as whether they enhance the recall of the memory material from which they are constructed. However, to

current knowledge, they are also yet to be rigorously tested and verified with supporting a posteriori evidence – that dreams arise from memory reactivations in sleep remains just an idea – nor do they provide any suggestions for how this is to be done. It is like supplying the blueprints of a bridge that could connect dreaming research with memory consolidation research, but without providing the tools or instructions needed to assemble it. However, a possible toolkit does exist in the form of a precise and elegant method called Targeted Memory Reactivation (TMR).

4. Testing the theoretical models with targeted memory reactivation (TMR)

4.1. Reactivating memories in dreams using TMR

Targeted Memory Reactivation involves first the learning of new information whilst being exposed to a particular sensory stimulus, most often an odour or sounds. Then during certain moments of post-learning sleep, most often NREM sleep, this sensory stimulus is re-applied at a level below the awakening threshold. The sleeping brain is able to register these sensory cues, and if they have been suitably contextually associated with what was learned, the cues can then trigger reactivations of these memories. These memory reactivations in sleep are believed to be a driving force behind the process of consolidation (Born & Wilhelm, 2012; Rasch & Born, 2008), facilitating the consolidation or integration of newly acquired memories by way of hippocampal-neocortical communication. This reactivation often happens spontaneously and independently of TMR (Schreiner et al., 2021), but, with appropriate external cues, TMR can be used to trigger or at least influence which memories become reactivated, and these can be detectible in the sleep EEG (Abdellahi et al., 2023; Belal et al., 2018). When executed successfully, TMR can produce a modest but statistically significant boost to behavioural memory performance compared to a non-TMR condition (Hu et al., 2020; Lieber, 2019) for a variety of memories (e.g., Diekelmann et al., 2012; Rasch et al., 2007; Rudoy et al., 2009; Oudiette et al., 2013; Schreiner & Rasch, 2017). TMR is highly sensitive, capable of reactivating and consolidating even individual memories (e.g., Antony et al., 2012; Rudoy et al., 2009; Schönauer et al., 2014; Schreiner & Rasch, 2015), and can even promote integration and reorganisation of information, facilitating insight and generation of new knowledge from old, to foster the incubation of solutions to difficult problems and puzzles (e.g., Ritter et al., 2012; Sanders et al., 2019).

However, TMR is also a very delicate process, and sometimes the typical boosting effect it offers for memory has not occurred (e.g., Ashton et al., 2018; Batterink et al., 2017; Cordi et al., 2014; Hennies et al., 2017; Wilhelm et al., 2020). Reviews and *meta*-analyses (Hu et al., 2020; Lieber, 2019) suggest there are a range of factors which can influence the success of TMR, including the modality of the cue, the type of task and memory being reactivated, the sleep stage of stimulation, and how well-learned the memory was before sleeping. However, it may have the greatest effects when targeted very precisely to the up states of slow waves, in what is termed a 'closed-loop' approach (e.g., Ngo & Staresina, 2022; Shimizu et al., 2018).

As with general sleep and memory research, however, dreams have been almost completely ignored in TMR research,[7] and go unmentioned in TMR review papers and *meta*-analyses (Cellini & Capuozzo, 2018; Hu et al., 2020; Klinzing & Diekelmann, 2019; Lewis & Bandor, 2019; Lieber, 2019; Schouten et al., 2017). However, very recently, Carbone and Diekelmann (2024) have included a section in their review paper about the known evidence so far for affecting dream content with TMR, which may promisingly suggest further attention from now on. Additionally, Oudiette and Paller (2013) acknowledged that sensory cues like those used in TMR designs have the capacity to influence dream content, citing a range of dream research which attempted to influence and manipulate real-time dream content with sounds and smells (e.g., Berger, 1963; Dement & Wolpert, 1958; Okabe et al., 2018; 2020; Schredl et al., 2009; Trotter et al., 1988),[8] but they do not address in detail whether dreaming plays a role in memory consolidation, stating that it is beyond the scope of their review, and do not develop any real argument for pursuing it. As it stands, most TMR researchers have neither explored nor acknowledged the possibility that their TMR cues might be incorporated into ongoing dreams, and have therefore never attempted to determine whether the memories their cues purportedly reactivated were in any way apparent or experienced as dream imagery. In return, the models of dreaming and memory consolidation previously discussed (Section 3) also do not make any mention of how TMR fits into their mechanisms, or incorporate the method or effects of TMR explicitly, but TMR may provide a key to testing them. It can be inferred that if the memory reactivation processes taking place during sleep influence dream content, and that these memory reactivation processes can in turn be influenced by TMR, then it is a logical extension that TMR can influence dream content as well. The dreams from stages of cued sleep may reflect the memories associated with that cue, or incorporate the specific TMR cue itself in a way that pertains to the memory.

Some limited evidence does exist that TMR-style cues can reactivate associated memories in dream content and consciousness, and these studies are few enough that they may be examined each in detail here. The earliest known study is that of De Koninck and Koulack (1975), who had their participants watch an emotionally stressful film before going to bed. Parts of the film's soundtrack were played again while participants were in REM sleep, akin to TMR procedures but decades before any such procedures were formally standardised. This seemed to result in more dream content relating to the film, but the original aim of this study was not to test memory

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[7] However a recent study by Nicosia & Balota (2022) has made some contributions by exploring waking mind-wandering with thought probes in reaction to memory cues provided during wakefulness. Their general conclusion was that there was a consistent effect of these cues in promoting mind-wandering about the learned materials, and that this had an implicit effect on recall performance (in terms of reaction time). If mind-wandering is related to REM dreaming as Fox et al. (2013) suggest, then this is an important lesson that could be transferred to TMR-dreaming studies.

[8] For a recent systematic review of this branch of dream engineering literature, see Salvesen et al. (2023).

for the film content, rather to assess whether REM dreams played an emotional regulation role, reducing the perceived stress when viewing an emotional film a second time if that film was dreamt about. In actuality, the opposite effect was found; dreaming about the film seemed to *increase* anxiety at the post-sleep showing. Viewing this study from a modern perspective with awareness of TMR, it appears to show that external cueing can be successful at reactivating associated memories in REM dream content, but this study cannot conclude whether this is beneficial for the memory of that content, as that was never tested. Also, as with the study of Fiss et al. (1977), there were only four to eight participants in each experimental group of this study, which is likely not sufficient with regard to statistical power to draw any robust conclusions, nor are we aware that the findings have been replicated since.

A study of a slightly different design by Hoelscher et al. (1981) investigated the responsiveness of dreams to external stimulation based on the personal significance of the stimulus to the dreamer. They presented auditory verbal stimuli to sleeping participants in Stage 2 and REM sleep, and these stimuli either bore some relation to the individual participants' personal concerns or no such relation, as determined through life questionnaire responses before they went to sleep (e.g., the name of a romantic partner). It was judged that the concern-related stimuli incorporated into REM dreams significantly more often than the non-concern stimuli compared to baseline dream content, but the same could not be concluded for Stage 2 dreams due to insufficient dream recall from that stage of sleep. Therefore, it seems that ongoing personal concerns were selectively reactivated in dream content by relevant auditory cues due to their salience. Since the sleeping brain is able to distinguish and react accordingly to the semantic meaning of auditory stimuli (Andrillon & Kouider, 2016; Kouider et al., 2014), and since we also tend to dream more about our major concerns in life (e.g., van Rijn et al., 2015), this holds implications for TMR studies if the information that is associated with the cue also becomes a present concern, making it even more likely to affect dream content. Again, however, this study cannot answer the question of whether this is beneficial for memory, as its aim was merely to manipulate dream content with concern and non-concern stimuli, not test any form of memory.

Smith and Hanke (2004) did test memory by having their participants learn a mirror tracing task in the presence of a ticking alarm clock, based on the procedure of an older study that successfully employed quasi-TMR techniques in this way (Smith & Weeden, 1990). These ticking sounds were presented again during, in their own words, 'quiet or maximal REM sleep', determined by the absence or presence of rapid eye movements, respectively. At retest one week later, there were no significant improvements on task performance, but the group that had the ticks presented during maximal REM reported significantly longer dreams (defined by number of words in the report) with more references to driving and recreation. The authors could only offer a tenuous, metaphorical interpretation of how these dreams could be related to the task, in that trying to keep a car on the road could be a metaphor for trying to keep between the lines on the mirror tracing task. This may or may not be a spurious finding.

The more recent study of Schredl et al. (2014) was directly inspired by established TMR knowledge and procedures with odours instead of sounds. Participants viewed a series of images of rural and urban scenes paired with either a negative or positive odour, which was then re-administered during REM sleep across the night (along with an odourless control stimulus), with the aim of reactivating these images in dreams. Dreams, when content-analysed, contained a greater number of rural topics if a congruent odour was presented compared to the odourless control stimulus, but there was no such effect for urban dream themes. The reasons why rural dream imagery, presumably related to the viewed rural images, was reactivated in dreams more than urban imagery is not clear, but the authors interpreted this as a partial confirmation of their goal, which was to attempt to reactivate memories in dream content with odours. However, this study did not complete the full TMR procedure with a follow-up post-sleep memory retest for the images, so again, whether the influenced dream content had any effect on memory consolidation for the viewed images is unknown.

Together, these four separate studies provide promising preliminary evidence that sound or odour cues are indeed capable of triggering dream content for memories that are associated with them (to some extent), and the effect may be even greater for emotional or concern-related stimuli, at least when cued during REM sleep. This holds important implications for TMR studies, and implies that the memory reactivations underlying consolidation, verified using a TMR protocol, may well be a major source of dream content.

Most recently, interest has started to develop in what has been termed 'Targeted Dream Reactivation' (Carr et al., 2020a; Horowitz et al., 2020). In the most complete attempt so far to reactivate memories in dreams and testing later performance using TMR, Picard-Deland et al. (2021) gave participants a novel procedural-memory task to complete in an immersive virtual reality (VR) video game environment: flying through a circuit of green rings to score points while avoiding red rings. Then during a 90-minute morning nap, the tones that accompanied flying through a green ring (associated with success in the task) were replayed to participants either in NREM Stage 2 or REM sleep, and at the end of the nap they were awoken from REM to obtain dream reports. They then played the flying task again after waking up, and their improvement was measured.

All participants improved their overall performance, but the group who had TMR applied during REM sleep improved significantly more than the control groups (who either had no sounds replayed during their nap or who stayed awake to read a book). TMR in NREM sleep had limited influence on performance, while TMR while awake did not improve performance beyond a nap or resting period without stimulation. Meanwhile, the TMR was concluded to have little noticeable effect on dream content; there were only 3 occasions across both TMR nap groups when the stimulus sounds incorporated themselves into dreams, and incorporation rates did not significantly differ between the two cued groups. But out of 105 recalled dream reports, 31 (36.5 %) contained possible incorporations of the VR task, and when this occurred in REM dreams, task performance improved significantly more than those who had no such dreams, and this was strongest for kinaesthetic elements of dream content (e.g., flying, falling or moving fast). Such elements of task content in NREM dreams were not related to performance improvement, despite there being a higher percentage of NREM dreams bearing task-related content. Waking thoughts about the task also occurred frequently in the wake groups, but these were unrelated to improvements. The most telling outcome, however, is this: while the TMR in REM appeared to have little effect on actual dream content, the greatest overall improvement on the task was seen as a *combination* of TMR during REM *and* reporting dreams of task-related content. The two seemingly independent phenomena produced the greatest outcome when they co-occurred.

We also conducted a comparable targeted dream reactivation paradigm, cuing in deep NREM sleep (Bloxham et al., 2021) during a

full night, but this did not influence outcomes of consolidation or dream incorporation. Cuing in a stage of sleep (SWS) that likely misaligned with the stage (REM) from which morning dreams were spontaneously recalled, added a challenge to the comparison of memory activations and concomitant mental activity.

All of these findings together point to REM sleep as an important stage of sleep for memory reactivation (or integration) in dream content. However, the recent *meta*-analysis by Hudachek and Wamsley (2023) reported a larger significant effect size for dream reports sampled from NREM sleep only (it was not able to specify exactly which stage of NREM sleep). These contrasting findings are difficult to explain at present, but a possibly pertinent compromise to be aware of is the apparent mis-match between sleep stages most conducive to TMR-based cueing and those most productive of dreaming. In traditional TMR studies, the enhancing effect is usually greatest when targeted to NREM sleep stages, particularly SWS, and minimal to ineffective, or qualitatively different, when targeted to REM (Cordi et al., 2014; Hu et al., 2020; Lehmann et al., 2016; Lieber, 2019; Rasch et al., 2007; Sterpenich et al., 2014). This may be explained by the elevated levels of neurotransmitters in REM which inhibit hippocampal-cortical communication (Payne & Nadel, 2004), and therefore systems memory consolidation. Yet SWS produces a reduced quality and quantity of dream recall compared to REM (Nielsen, 2000; Siclari et al., 2013), making it less convenient for sampling dreams. Meanwhile, REM is the stage most frequently targeted by the studies which aimed to influence dream content with external sensory stimulation (e.g., Berger, 1963; Okabe et al., 2018; Schredl et al., 2009; Trotter et al., 1988), due to its high likelihood for detailed dream recall. These may all be pragmatic choices, as it is harder to wake someone up when playing sounds to them in SWS due to the usually higher arousal threshold required to cause awakening, yet from a dreaming point of view we may be more responsive to external cues during REM sleep, especially when sleeping in a laboratory for the first time (Tamaki & Sasaki, 2019), and especially during tonic REM (Andrillon et al., 2017; Ermis et al., 2010; Koroma et al., 2020; Sallinen et al., 1996). These studies suggest that during phasic REM sleep, the sleeping brain is more preoccupied with endogenous dream imagery, but tonic REM offers brief pauses to monitor the surrounding real-world environment for danger cues and other disturbances. Therefore, if TMR is attempted in REM, then it may be best targeted to the tonic periods of REM when the brain is better able to detect them, albeit running a higher risk of causing an awakening.

As such, there might be a difficult trade-off between achieving the different aims of getting the best effects of TMR and obtaining a suitable number of high-quality dream reports to examine for evidence of memory reactivations as produced by the TMR cues. It again raises the possibility that memory reactivations and dreams, while related, may have independent effects. Nevertheless, benefits with REM TMR could be possible; some very recent work has claimed that memory reactivations are detectible in REM sleep in response to TMR (Abdellahi et al., 2023),[9] and some memories may be reinstated in the beta activity of REM sleep, possibly showing up in dreams (Kumral et al., 2023). This remains to be further explored, replicated and confirmed, but if it proves that this activity at least correlates with dreaming of the identified material, verified with dream reports, then it could offer a way around the problem of failing to recall a dream report, and those who remember nothing from the night need not be excluded from analysis. Finally, the efficacy of TMR depends on being able to activate the brain in specific ways, and this itself depends on the state of the brain during a particular phase of sleep. The cue must be dependent on that brain activity, not vice versa; olfactory cueing, for example, would be unsuitable during a stage of sleep when olfactory perception is being inhibited by the sleeping brain.

Altogether, this research provides a promising direction to pursue in the question of whether there is any link between memory consolidation in sleep and dreaming. Whilst the theoretical models of dreaming and consolidation (Horton & Malinowski, 2015; Murkar, 2013; Murkar et al., 2014; Paller & Voss, 2004; Payne & Nadel, 2004; Wamsley, 2014; Wamsley & Stickgold, 2010; 2011; Zhang, 2009) do not incorporate the method or effects of TMR, TMR may nevertheless provide a means of testing them. The first forays into investigating this have provided partial support for this reasoning, but there is still much more to do.

4.2. Recommended future directions for targeted dream reactivation research

TMR has much to offer dreaming and memory research, but by itself it cannot address all the methodological problems and obstacles we have identified (Section 2.2). In order to be most certain of the results that could be produced, some careful thought will need to be given to its execution, and we propose a combination of transparent methods and choices to help achieve these aims and get the best use from it (see Box 2 for a summary of our recommendations, ideas, and choices to be aware of).

4.2.1. Addressing the power problem

Firstly, as evaluated in Section 4.1, TMR may help to address the low incorporation rates typically seen by increasing the probability of dreaming about the target material, and thus increasing statistical power with more participants/instances of such incorporations. Indeed, a weakness of the existing studies (Table 1) is that they relied on spontaneous occurrence of task-related dream activity, but TMR can introduce the experimental manipulation of dream content as an independent variable. As further discussed in Section 4.2.3, however, it must be anticipated that memories, if reactivated in dreams, still may not appear veridically or unambiguously in dream content, therefore a rigorous incorporation identification procedure must also be utilised as part of this approach.

Further avoidance of data shortage could also be achieved by carefully sampling participants who already have good dream recall (frequency and detail). This would help ensure that a suitably large number of dreams are remembered, and since frequent dream recallers also seem to exhibit larger neurological reactions to external stimuli (Eichenlaub et al., 2014; Vallat et al., 2017), this might also yield greater TDR effects. However, a word of caution, it may not be appropriate to generalise the effects and data gained from

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[9] Although there was no memory enhancing benefit of TMR in this case, and no dream reports were collected to confirm if the reactivated memories were apparent in dream content.

frequent dream recallers to others; high dream recallers seem to exhibit different neurophysiological profiles than low dream recallers, including increased connectivity in the DMN (Vallat et al., 2022), suggesting that their brains may be behaving in ways that are different to those of typical individuals within the general population.

If it is not possible to source frequent dream recallers, then, as also suggested by Hudachek and Wamsley (2023), increasing the number of awakenings across the night to increase the chances of obtaining a dream report is a viable alternative, such as with the serial awakening paradigm (e.g., Noreika et al., 2009; Picard-Deland et al., 2023b; Siclari et al., 2013). This results in more sleep disruption, but when done in moderation, this does not appear to abolish the memory consolidation effects that sleep provides (Schoch et al., 2019). Since such repeated measures designs are a recognised way to increase power, especially when research funds are limited (Allison et al., 1997), this seems like an ideal route to take in dream research, when running multiple overnight studies per participant will become expensive, and especially if frequent and detailed dream recallers make up the sample. While this may help increase the number of dream reports available to analysis, it is still no guarantee that it will increase the incorporation rate of the task, unless combined with a TMR procedure. It could also offer exploration of effects between different stages of sleep, for as also described by Hudachek and Wamsley (2023), the associations between dreaming and memory consolidation effects appear to be strongest in NREM sleep, but they were not able to tease apart which NREM stages precisely; this is especially important to understand, given that there are intra-stage differences and sub-stages within each of these stages, e.g., there are at least six different wave forms within Stage 1 sleep alone (Hori et al., 1994).

Running overnight experiments in a laboratory is unavoidably costly in both time and resources, and this may also produce limits on how many participants can feasibly be tested, indirectly contributing to less data that can be gathered. Hudachek and Wamsley (2023) also identified this problem in their *meta*-analysis. But Smith and Little (2018) provide an intriguing argument that contests the idea that large sample sizes are the only way to achieve high levels of statistical power, arguing that it is achievable even in very small sample sizes. They place more importance on strong measurement methods, which can effectively control random error variances, and which are based on strong, non-ordinal, quantitative models. Then, rather than asking if performance between two groups differs significantly, they emphasise asking whether the model agrees with the data that was collected within the limits of measurement precision. Since dreaming is a very private and individualised experience, such an approach could be useful, for we can still learn a lot from a single individual's dream activity, preserve the unique qualitative individual differences that may occur between dreamers, as well as the similarities, and maybe even focus on replicating group effects on the individual level, rather than vice versa. This is important because not every dreamer can be expected to dream about the same learning experience, nor respond to a dream incorporation or stimulation, in exactly the same way. Again, this could perhaps be best achieved using the serial awakening paradigm on individuals with frequent and detailed dream recall.

4.2.2. Lucid dreaming, dream engineering and dream incubation

Lucid dreaming could be another alternative way forwards, in helping to increase incorporation rates volitionally and with more control. Despite the rarity of talented lucid dreamers available as research participants, a recent study was able to induce lucid dreams in the laboratory quite reliably, even in novices who had never had a lucid dream before, by training them to associate sound and light cues with performing critical reality tests (Carr et al., 2020b). Effectively, these sensory cues served as yet another targeted memory reactivation, acting as a reminder to participants to check if they are dreaming or not, thus prompting lucidity when they were incorporated into dreams. With practice, and if also combined with task-related sensory cues, lucid dreamers could summon task-related content or actions within their dream, and there is some evidence that practising skills lucidly can lead to improved waking skills and behaviours (Erlacher & Schredl, 2010; Erlacher et al., 2012; Schädlich et al., 2017; Stumbrys et al., 2016). However, in a recent *meta*-analysis (Bonamino et al., 2023), this effect, while positive and of medium size, was not significant, possibly explainable due to the very small number of such studies that have been conducted, all with rather small sample sizes, and a lack of controlled laboratory measurements. This approach is also far from fool-proof, as even talented lucid dreamers may not be able to fully control all aspects of their lucid dreams, which can affect their dream performance (Schädlich et al., 2017), and since lucid dreaming is an atypical state of sleep and consciousness (Baird et al., 2022), it may not be generalisable to the more frequently occurring non-lucid sleep and dream experience. There is even some concern regarding the hitherto unknown effects of frequent and long-term lucid dreaming on normal sleep patterns and functions (Vallat & Ruby, 2019).

A related alternative to the lucid dreaming approach could be Targeted Dream Incubation (TDI), a process similar to TMR but which concentrates on sensory prompting during the hypnagogic sleep onset period (N1) with the intention of crafting desired dream content. This provides another means of exerting greater control or influence over emerging dream content in the transition from wakefulness into sleep. Technology now exists to allow for automatic and repeated TDI, and evidence so far shows that it is capable of influencing hypnagogic dream content for suggested themes (Horowitz et al., 2020) and that this influenced hypnagogic imagery can predict heightened creativity (Horowitz et al., 2023). Whether this is beneficial for memory consolidation or not as well is still to be confirmed, given that N1 sleep, with its typically very short duration, has limited opportunity to leave a mark in the memory consolidation process. Whilst even a very short nap of less than ten minutes (including both N1 and N2) has been seen to have a small effect (e.g., Lahl et al., 2008), more recently, N1 in isolation was associated with increased forgetting in a spatial memory task (Lacaux et al., 2022),[10] suggesting that N1 by itself may not benefit memory consolidation, at least for items that were more difficult to encode at learning. N1 can be a very diverse stage of sleep with numerous electrophysiological sub-phases (Stenstrom et al., 2012), and studies

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[10] This study also collected dream and mentation reports, but again, not enough with unambiguous task-relevant content to allow a robust analysis. Nevertheless, both dreaming in general and thinking about the task while awake were unrelated to memory performance.

Box 2

Checklist for Targeted Dream Reactivation Studies

Here we recommend a series of steps to be met and choices to be considered when designing and executing future Targeted Dream Reactivation (TDR) studies. Note, this is not a comprehensive or exhaustive list, but each choice is likely to have effects on the outcomes and conclusions.

Theoretical Framework and Hypotheses

- What is the hypothesis, what do we expect to happen, and why do we expect this to happen? Which theory is this hypothesis derived from, and is this a good fit for the research question and planned analyses? We ought to be able to understand and explain the effect as well as just show that it happens, so having a theoretical starting point can help achieve this and provide guidance.

Design choices

- Select a suitable learning task. What will your participants do? This task ought to:
  o Have a clear measurable component that is dependent on some form of memory to allow the user to improve through practice (online and offline).
  o Have a clear sensory element that can serve as a suitable TMR cue. Contextual sound effects are perhaps better suited for affecting dream content than odours.
  o Be novel and distinctive enough so as to be clearly identifiable in dream reports and not be confused with incidental dream content (i.e. producing a false positive incorporation). We recommend foreign-language vocabulary learning tasks or virtual-reality spatial navigation tasks.
- Participants should have good dream recall. This is to help ensure high quality data (i.e. multiple detailed dream reports). Aim for as many participants as possible, using the effect size estimates provided by Hudachek and Wamsley (2023) for guidance to ensure reaching suitable power levels.
  o Collecting a baseline sample of dream reports with which to compare the TMR-stimulated dream reports would be helpful to further prevent misidentification of incidental dream content. Alternatively, apply a non-stimulated control condition, ideally within-subjects across a single night (i.e. some REM periods stimulated, some not), in a serial awakening paradigm.
- Awaken participants soon (~30 seconds) after TMR stimulation to obtain a dream report. This should be done several times across the course of a sleep period (a full night's sleep will be more appropriate for this rather than a daytime nap of 1-2 hours) in order to meet requirements of statistical power, such as with a serial awakening paradigm. The aim is to increase the amount of data in the form of more dream reports per participant, and increasing the probability of obtaining reports which bear the desired take-relevant content.

Analytical choices

- The coding process: Be clear on what counts as a definite incorporation of the memory task and what does not. Seeking insight from the dreamer themselves, who knows their own dreams better than a blind coder would, especially if they already have good dream recall, could be useful in expelling any doubts. However, be aware that this may also be a source of bias, such as if the participant guesses or assumes the hypothesis, and this affects the way they engage with the coding or discussion. This is perhaps best utilised in combination with external rating, perhaps making use of new Artificial Intelligence tools to automate the coding process, if overall patterns within the dream content are of interest.

The analysis process: Based on the coding procedure chosen, decide on how dreams and memory performance are to be co-analysed. Be clear on the reasons for your choice, and understand that an alternative choice may lead to different outcomes. We specifically recommend, following the proposals of theoretical models (Section 3) and our critique of the EH (Fig. 2), not to rely solely on a quantitative memory change or dichotomous categorising of dreaming of the task vs. not. This is perhaps best combined by building upon the EEG-decoding approaches by Abdellahi et al., (2023) and Kumral et al., (2023), tying together the electrophysiological and neurological basis of dream experience and particular content (Horton, 2023).

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have reported that early-night or even sleep-onset dream imagery related to a learning task can correlate with later improved performance on that task (Fogel et al., 2018; Stenstrom et al., 2012; Stickgold et al., 2000; Wamsley et al., 2010a). A possible explanation lies in the NExTUP model of Zadra and Stickgold (2021), who argue that the hypnagogic imagery could act as a 'tagging' step in the process, selecting or priming particular memories for processing and broader association among semantic networks later on in sleep, an idea which still needs to be empirically verified. However the creative benefits of hypnagogic dream content appear to be evident (Horowitz et al., 2023; Lacaux et al., 2021), and there is even some evidence that presenting an odour relevant to a creative task in TMR fashion later in sleep can facilitate the finding of creative solutions to those tasks (Ritter et al., 2012; Sanders et al., 2019). While it remains unknown if TDI can be a benefit to memory consolidation, it nevertheless appears to stand as an alternative means to increase

the probability of dreaming of memory- or task-related imagery at sleep onset, maybe contributing an indirect effect to memory by means of creativity or forgetting.

4.2.3. Task selection and identifying valid incorporations

The type of memory or learning task to use will also require careful attention. The typical sorts of tasks used in traditional memory consolidation studies, such as declarative lists of word or picture pairs or sentence learning (Cipolli et al., 2001; 2004; Schoch et al., 2019), or fine motor procedural tasks like mirror tracing (Schredl & Erlacher, 2010), while well-suited and validated for studying discrete memory abilities, are perhaps less suitable for studying wake-dream continuity. They may not be vivid or engaging enough to produce a strong incorporation effect, or they may not be distinctly recognisable enough to differentiate clearly from other dream content. However, there are other forms of tasks which may be both memory-sensitive and impactful enough to recognisably influence dream content.

The ongoing development of virtual reality technology (e.g., Picard-Deland et al., 2019; 2020; 2021; Ribeiro et al., 2021; Shimizu et al., 2018; Stenstrom, 2010) may offer a better alternative, providing richly detailed and immersive environments which could lend themselves to a very novel, memorable and episodic experience. The more immersive, interactive nature and high graphical fidelity provided by VR head-mounted displays have been previously identified as a predictor of dream incorporation compared to playing on a non-VR setup (Gackenbach et al., 2011; Saucier, 2006). VR can be highly controllable, allowing comprehensive, detailed creation of bespoke environments and activities, and is suitable, for example, to test forms of memory such as spatial navigation through a novel environment, which has already seen much use in previous dreaming and memory consolidation studies (Fogel et al., 2018; Nguyen et al., 2013; Solomonova et al., 2015; Stamm et al., 2014; Stenstrom, 2010; Wamsley et al., 2010b; 2016; Wamsley & Stickgold, 2019). This type of memory is also easily applicable to real-world learning and everyday life and activity (e.g., route-planning when driving or walking through new cities and other real-world environments). Shimizu et al. (2018) have shown that this type of task is sensitive to TMR effects.

Another ecologically valid recommendation is language learning, which has already been the subject of much TMR experimentation (Schreiner & Rasch, 2017). Even though language and speech are a common feature of dreams (Dollnick & Schredl, 2024; Kilroe, 2001; Shimizu & Inoue, 1986; Zadra et al., 1998), learning a new language, even living in a multilingual environment, has recognisable effects on both REM sleep and dream content (De Koninck et al., 1988; 1989; 1990; Foulkes et al., 1993; Lum & Wade, 2016; Šarčanin, 2018; Sicard & de Bot, 2013). As the world becomes increasingly multicultural and internationally connected, many people are multilingual or aspire to learn new languages, so understanding how one learns and uses languages, and more generally how one acculturates themselves, is an important topic. By applying foreign language audio cues during sleep (as done in language TMR studies), and then awakening the sleeper for a dream report shortly thereafter, it can be attempted to determine for example if the dream report contains instances of a recognisably foreign language. It may be more difficult, however, to verify if the language that occurs in a dream is grammatically and linguistically correct and meaningful, depending on how well the dreamer is able to remember exactly what was uttered in their dream. Language also has both declarative elements (learning the meanings of individual words) and non-declarative elements (applying grammar and stringing coherent sentences together), both of which may be worth investigating.

These types of tasks, given their distinctive and easily identifiable formats, should help in reducing the chances of false positive incorporations in dream content, another issue to which many of the previous empirical studies have been susceptible. However, even if TMR is successful at reactivating memories in dream content, the reactivations may still be far from unambiguous. Since dreams so rarely replay complete memories episodically (Fosse et al., 2003; Malinowski & Horton, 2014a), and the reactivated patterns of learning-related brain activity (at least in rats) are often temporally accelerated (Euston et al., 2007; Lee & Wilson, 2002), it is fair to assume that the reactivated experience will not be fully relived in dream content. The dreams of REM sleep, in which there are also elevated levels of neurotransmitters which can inhibit hippocampal-neocortical communication (Payne & Nadel, 2004), may not reflect the consolidation process accurately. Dreams may instead be involved in creating hyperassociative links between memories (Horton & Malinowski, 2015), integrating new experiences into existing autobiographical networks (Solomonova, 2018), or exploring relevant alternative scenarios (Zadra & Stickgold, 2021).[11] If this is true, indirect incorporations may still result and may still be relevant, but are subject to interpretation during the coding process. It will therefore still be necessary to agree on clear guidelines for coding and identifying possible incorporations; as the stringency and leniency of these guidelines can have a direct effect on the incorporation rate, reducing or increasing it respectively. In the case of absence of dream recall, neural recordings may be made to measure for the presence of replay or reactivation of learning related brain activity (e.g., Abdellahi et al., 2023; Kumral et al., 2023; Maquet et al., 2000; Michelmann et al., 2016; 2018; Parish et al., 2021; Peigneux et al., 2004; Staudigl & Hanslmayr, 2019), or this data may complement dream report data to help tease apart indirect incorporations from unrelated content. We provide an updated theoretical illustration to depict the relationships we discuss here (Fig. 3), which expands upon the central assumption illustrated within Fig. 1 that memory consolidation may produce dreams.

As for the modality of the TMR cue itself, sounds are perhaps better suited than odours; while odours pose a lesser chance of causing an unintentional awakening, and can reliably reactivate memories (Diekelmann et al., 2012; Rasch et al., 2007; Shanahan & Gottfried, 2017), their effects on dream content are not always obvious. Direct incorporation rates and odour perceptions in dreams are uncommon, and contradictory effects have been reported regarding the emotional tone of the dream in response to the odour (Okabe et al., 2018; 2020; Schredl et al., 2009; Trotter et al., 1988). Auditory stimuli have a more noticeable effect on dream content and tend

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[11] All of these points are also favoured by Hartmann (2010).

to produce higher incorporation rates than odours (Salvesen et al., 2023; Schredl & Stuck, 2009), and may be better for reactivating specific, individual memories, but may cause greater chance of sleep disruption. The type of cue must also align with the types of brain activity that are present during the targeted stages of sleep; e.g., olfactory cueing would be of no use if the sleeping brain is inhibiting olfactory perception (Carskadon & Herz, 2004; Gaeta & Wilson, 2022).

In combination with this, it will always be wise to collect pre-task dream content to serve as a baseline comparison. Coding practices need to be established carefully, with clear agreement on what counts as a valid incorporation of the learning task or material and what does not, and why. Blind coding of both baseline and stimulated dreams will be useful to help ensure objectivity, but in ambiguous cases, the input from the dreamer themselves could well prove useful, and should not be ignored.

5. Conclusions

Dreaming and memory consolidation are seldom studied together, and when they are, they are not always studied consistently, with a diverse range of different learning tasks and analytical approaches employed by researchers and authors. They stand as two distinct pathways with different destinations, each walked by different researchers who have different interests and goals. Nevertheless, some have noticed that there is space enough between these paths for overlaps to exist, and the construction of a bridge to connect them along these lines appears possible. The foundations and blueprints of this bridge, the major theoretical assumption encapsulated by a number of key models and writings (Horton & Malinowski, 2015; Murkar, 2013; Murkar et al., 2014; Payne & Nadel, 2004; Wamsley, 2014; Wamsley & Stickgold, 2010; 2011; Zhang, 2009), is that the reactivation of memories during sleep simultaneously contributes to the consolidation of those memories and some of the formations of dream content. In other words, the sleeping brain achieves two different outputs by the same process: consolidation on the neurological level, and dreams on the psychological, subjective level which provide a limited window into parts of this process.

However, these models and their assumptions remain unverified and largely unaddressed by published empirical studies. The few researchers who have attempted to cross this bridgeable divide between dreaming and memory consolidation have chosen to go by a different route. Rather than determining if memory reactivations are the shared source of both memory consolidation and wake-dream continuity (as the models suggest), they have instead focussed on testing for an association between dreaming of learning-related material and subsequent memory improvement or enhancement. We are critical of this approach, for as we have outlined, it sets up a number of difficult methodological obstacles which stand in the way of a confident answer, owing to the inherent challenges of studying and controlling dreams directly.

We argue for a change, a paradigm shift, in the way dreams are studied with regard to memory consolidation. We propose a new focus on ascertaining if the mechanisms of dream production are shared with those of memory consolidation, as the theoretical models suggest. The EH cannot be tested robustly until there is a sure way to obtain a large enough number of certain dream incorporations to satisfy demands of statistical power. As studies on this matter have shown, it is very difficult to influence and control dream content in the desired way, and there a multiple sources of random error variance. But TMR may hold a means to achieve this, the toolkit for constructing the bridge.

The method of TMR allows for precise targeted reactivations of individual memories, has been reliably linked to memory consolidation processes and effects in sleep, and it also has the potential to affect ongoing dream content with its sensory cues. These cues might reactivate the memory material, or related material, in dream content (De Koninck & Koulack, 1975; Schredl et al., 2014), and may thus also increase the probability of dreaming about the target learned material. TMR progresses dream science by allowing for dream content to be manipulated as an independent variable, and although this will not solve all methodological challenges, they may be surmounted in time with improved dream sampling, technological developments and accessibility efforts. By conducting more TMR studies, combined with post-cueing awakenings to assess dream content (Targeted Dream Reactivation, or TDR), the aforementioned theoretical models may be tested, perhaps in an easier way than pursuing the EH. In this way, we can become surer if what we dream about is indeed connected to verifiable memory reactivation/consolidation processes that take place in sleep.

In conclusion, this article emphasises the need for stronger critical reflection, theoretical guidance, and methodological rigour in the field of memory and dreaming research, with attention to how and why we ask the questions that we do, and awareness of the choices that we make in pursuing answers to our research question. A new roadmap does exist in the form of several detailed, well-founded theoretical models and writings, but it points in a slightly different direction to the one that has been doggedly pursued. We have provided a synthesis of these models, and testing them, by determining the relation of memory reactivations to dream content, is the proposed direction to take now. The technique of TMR provides the most promising toolset that will allow this path to be explored, combining controlled, targeted reactivation of learned material during sleep and systematic dream sampling and content analysis for components of the learned material. While it should be anticipated that this path might also ultimately lead to an empty dead end, it can still be mapped so that we will know what lies or does not lie over there, and evaluate whether it was worth exploring, and yet another unexplored path might be discovered along the way. This, we believe, is the way forwards.

CRediT authorship contribution statement

Anthony Bloxham: Writing – review & editing, Writing – original draft, Visualization, Project administration, Investigation, Conceptualization. **Caroline Horton:** Writing – review & editing, Visualization, Supervision, Conceptualization.
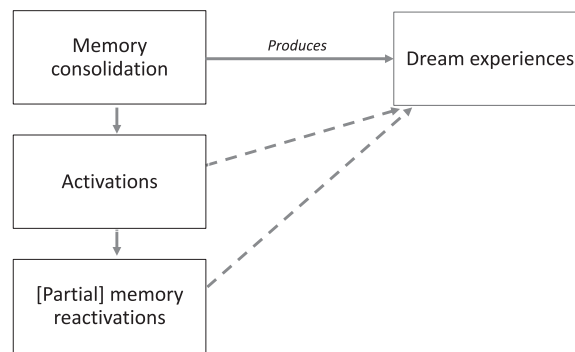
Fig. 3. An updated theoretical illustration of the relationships between memory reactivations and dream experiences, expanding upon our ideas as illustrated in Fig. 1, whereby memory consolidation may produce dream experiences, both directly (via activated memories being consolidated) and indirectly (via associated memory elements being activated, akin to spreading activation models). All activated memory elements, whether via memory consolidation mechanisms or associations thereof, yield mentation, giving rise to dream experiences that comprise different memory sources simultaneously. This accounts for the characteristic of hyperassociativity in dreams.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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