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Learning during sleep in humans – A historical review

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ABSTRACT

Sleep helps to consolidate previously acquired memories. Whether new information such as languages and other useful skills can also be learned during sleep has been debated for over a century, however, the sporadic studies' different objectives and varied methodologies make it difficult to draw definitive conclusions. This review provides a comprehensive overview of the history of sleep learning research conducted in humans, from its empirical beginnings in the 1940s to the present day. Synthesizing the findings from 51 research papers, we show that several studies support the notion that simpler forms of learning, such as habituation and conditioning, are possible during sleep. In contrast, the findings for more complex, applied learning (e.g., learning a new language during sleep) are more divergent. While there is often an indication of processing and learning during sleep when looking at neural markers, behavioral evidence for the transfer of new knowledge to wake remains inconclusive. We close by critically examining the limitations and assumptions that have contributed to the discrepancies in the literature and highlight promising new directions in the field.

1. Introduction

While we understand the mechanisms of memory consolidation during sleep in increasing detail, the wider public is often more interested in a more practical question: can we learn new languages and other helpful skills during sleep, rather than just consolidating information acquired during wakefulness? This is not a new question: already a century ago, Hugo Gernsback described a device called the "Hypnobioscope" in his science fiction novel "Ralph 124C 41+", which transmits information via a headband to the sleeping brain, enabling people to learn not only when awake but also when asleep [1]. Similarly, in Aldous Huxley's novel "Brave New World," sleep-learning was employed to condition individuals during sleep, making them accept society's norms [2]. In the following decades, several scientific attempts have been initiated to make this science fiction staple a reality. However, despite continuous efforts from researchers, we do not have a "Hypnobioscope" today, and our learning is limited to our waking hours.

Memory formation involves the encoding, consolidation, retrieval, and reconsolidation of memories. The consolidation process strengthens, reorganizes, and integrates newly encoded memories [3]. Memory has been classified according to the nature of the information processed and the level of conscious awareness involved in encoding and retrieval processes. Declarative learning involves acquiring explicit knowledge, such as facts and events, which can be consciously recalled. Non-declarative learning, on the other hand, involves acquiring implicit knowledge, such as motor skills and habits, which are typically processed without conscious awareness [4].

While sleep is accompanied by a partial or complete loss of consciousness, the brain can still process external stimuli while asleep [5,6] – a necessary condition for learning to occur. Human sleep is composed of a series of 90-min cycles, during which the brain alternates between non-rapid eye movement (NREM) sleep and rapid eye movement (REM) sleep [7]. These different stages of sleep are associated with distinct patterns of brain activity and are characterized by unique electrophysiological events such as sleep spindles or slow oscillations which likely have different capacities for processing sensory information and facilitating learning. A comprehensive overview of sleep stages and their

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Abbreviations: AASM, American Association of Sleep Medicine; CR, Conditioned Response; CS, Conditioned Stimulus; EEG, Electroencephalography; ERP, Event-related potentials; NREM, Non-rapid eye movement; REM, Rapid eye movement; UR, Unconditioned response.

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Glossary of terms

Non-declarative Memory Memories that are formed and/or retrieved unconsciously and cannot easily be articulated, such as skills. Also referred to as implicit memory

Declarative Memory Memories that are formed and/or retrieved consciously and can be verbally articulated. It includes memories of facts and (personal) events. Also referred to as explicit memory

K-complexes K-complexes are sharp, high-voltage biphasic waves in the EEG that last for at least 0.5 s, with a short positive voltage peak at about 200 ms, a large negative complex at around 550 ms, and a long-lasting positive peak at about 900 ms. They can be either spontaneous or triggered by stimuli

Up- and down-states During slow-wave sleep, the thalamocortical system displays fluctuating up-states and down-states. Up-states are periods in which membranes are depolarized, with increased neuronal activity and down-states are periods in which membranes are hyperpolarized, with reduced neuronal activity

Lucid dreaming Lucid dreaming is a state of consciousness in which the dreamer is aware that they are dreaming. While the exact mechanisms underlying lucid dreaming are not fully understood, it is believed to be related to changes in brain activity that occur during the rapid eye movement (REM) stage of sleep

differentiating features based on various sleep scoring methods is presented in Table S1.

This article will delve into the history of sleep learning research, exploring the achievements and challenges scientists have faced in their quest to make the “Hypnobioscope” a reality. While some evidence supports sleep learning in non-human animals [8–10], this article focuses solely on human studies. We will comprehensively review various types of learning, including habituation, conditioning, perceptual and statistical learning, procedural learning, and verbal learning. Furthermore, we will distinguish between the different sleep stages during which learning occurred. By examining the articles through the lens of sleep and learning taxonomies, we aim to provide a comprehensive understanding of how the brain processes new information during different sleep phases. Moreover, we will highlight the differences in assumptions and methodologies of previous studies and offer future directions for research in this field. Fig. 1 illustrates the timeline of the sleep learning research.

2. Habituation

Habituation, one of the simplest forms of learning, occurs when the immediate reaction to a novel stimulus, known as the orienting response, diminishes after repeated exposures [8]. Habituation during sleep has been studied in five experiments from 1960 to 1975, with promising results [9–13].

Typically, these studies—comprising one case study and four pre-, quasi-, or experimental studies—repeatedly presented auditory stimuli to participants during sleep while measuring different orienting responses such as heart rate (Table 1, and for comprehensive details, see Table S2). All the studies used EEG to objectively confirm the participants’ sleep and scored sleep stages systematically. Moreover, differing methods were used to measure habituation. While some settled for visual inspection of the response curves, others fitted linear or exponential curves to the data to check for a significant decrease in orienting responses.

The first study investigating habituation during NREM sleep reported the habituation of K-complexes in the participants in response to names [9], but this was not replicated by a second study which showed habituation of various orienting responses, including K-complexes, to a tone only during wakefulness [10]. It is important to note that in the first study, a sedative pharmaceutical drug was used to induce sleep in sleep-deprived participants.

Two subsequent studies tried to optimize stimulus parameters to increase habituation during sleep. During a pilot study, autonomic responses showed habituation—skin potential across all sleep stages and heart rate during NREM sleep—regardless of interstimulus duration or regularity [11]. The K-complexes, however, habituated only in response to shorter interstimulus intervals during N2. Further, a weak stimulus (a low-frequency and short-duration tone) with relatively short interstimulus intervals was able to induce habituation of heart rate and finger plethysmograph responses in wake and all sleep stages [12]. The final study observed habituation of autonomic responses only during N2 sleep, which did not transfer into wakefulness or subsequent stages of sleep, including N2 sleep [13].

3. Conditioning

Classical conditioning is a type of associative learning in which an unconditioned stimulus (US) that evokes an unconditioned response (UR) is coupled to a neutral stimulus (conditioned stimulus, CS) that

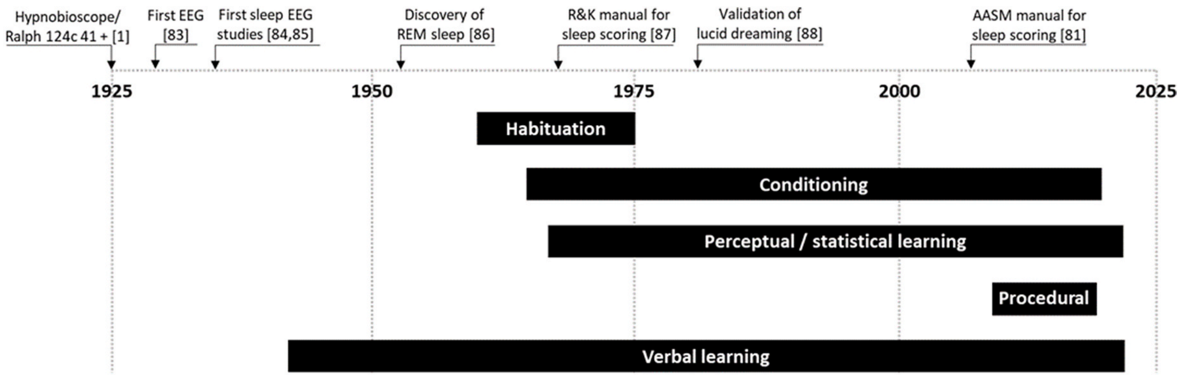

Fig. 1. Historical overview of the studies on learning during sleep within the framework of sleep research. AASM: American association of sleep medicine; EEG: Electroencephalography; R&K: Rechtschaffen & Kales [83–88].

Table 1
Studies on habituation during sleep 1960–1975.

Study Authors Year	Participants	Design (D) Objective (O)	Stimuli (S) Presentation time (PT)	Outcome measures (OM) Measurement time (MT)	Findings	Effectiveness
Oswald et al., 1960 [9]	10 sleep deprived adults	**D:** Pre-experimental post-test within-groups comparison **O:** Explore the different responses to participants' own names and others during sleep	**S:** Names **PT:** Sleep (C & D)	**OM:** Decrease in K-complexes **MT:** Sleep (C & D)	Habituation of K-complexes in NREM	+
Johnson and Lubin 1967 [10]	17 healthy adults (12 also received habituation tone in wakefulness)	**D:** Quasi-experimental between- and within-groups comparison **O:** Study ORs in wake and sleep	**S:** Tone **PT:** Sleep (all stages) & wakefulness	**OM:** Decrease in K-complexes, HR, RR, FP, SR, and SP **MT:** Sleep (all stages) & wakefulness	Habituation of all responses only in wakefulness	0
Firth 1973 [11]	3 healthy adults	**D:** Pilot multiple-case study **O:** Explore habituation in sleep optimizing stimuli properties	**S:** Tone **PT:** Sleep (all stages)	**OM:** Decrease in SP, HR, K-complexes, evoked alpha rhythms **MT:** Sleep (S2, S4 & REM)	Habituation of SP in all sleep stages, HR in NREM, K-complexes in S2 for short ISIs, alpha rhythms in REM (not clear for which ISIs)	+
McDonald and Carpenter 1975 [12]	46 healthy adults (Sleep = 46, Wake = 24)	**D:** Quasi-experimental post-test between- and within-groups comparison **O:** Study habituation in sleep, while optimizing stimuli properties	**S:** Habituation tone & dishabituation tone **PT:** Sleep (S2, S3, S4 & REM) & wakefulness	**OM:** Decrease in HR, SP, SR & FP **MT:** Sleep (S2, S3, S4 & REM) & wakefulness	Habituation, dishabituation, and spontaneous recovery of HR & FP in all states, SP & SR only in wakefulness	+
Johnson et al., 1975 [13]	46 healthy adults (Exp = 32, control = 15)	**D:** Experimental post-test between-groups comparison **O:** Study habituation and its state-dependency	**S:** Tone **PT:** Sleep (S2 & REM) & wakefulness	**OM:** Decrease in SR, SP, HR, FP & K-complexes **MT:** Sleep (S2 & REM) & wakefulness	Habituation of HR & FP in S2; no carry-over to wakefulness or later S2 periods	+

"+": effective; "0": not effective; D: Design; Exp: Experimental; FP: Finger plethysmograph; HR: Heart rate; Hz: Hertz; MT: Measurement time; NREM: Non-rapid eye movement sleep; O: Objective; OM: Outcome measures; OR: Orienting Response; S: Stimuli; PT: Presentation time; REM: Rapid eye movement sleep; RR: Respiratory rate; S: Seconds; SP: skin potential; SR: Skin resistance.

eventually will evoke the conditioned response (CR) [14]. Between 1965 and 2020, seven studies have aimed to demonstrate conditioning during sleep [15–21], by pairing auditory stimuli with shocks, air puffs, or odors, with all but two studies conducted within the last 15 years (Table 2, and for comprehensive details, see Table S3). All seven quasi-experimental or experimental studies objectively verified sleep, and six scored sleep systematically.

Two studies 30 years apart showed successful classical conditioning during sleep, including a transfer to wake, though the transfer was limited to N2 conditioning [15,16]. It is important to highlight that the first study utilized a sedative pharmaceutical drug to induce sleep. In the subsequent study, involving five participants, two exhibited indications of awakening during the conditioning process during N2 sleep.

Another study coupled pleasant and unpleasant odors (US) with different tones (CS) during sleep [18]. They showed that the sniff response (CR) to the two tones differed significantly during sleep, with a larger difference during REM sleep, but again transfer to wakefulness was limited to conditioning in NREM sleep. Notably, this study included a control group that did not undergo conditioning and demonstrated no significant differences in sniff responses to tones. However, the substantial disparity in participant numbers between the experimental and control groups reduces statistical power to identify significant effects within the control group. When a later publication analyzed the corresponding EEG data, it uncovered that the interaction between slow-waves, sleep spindles, and theta activity characterizes learning new associations during sleep [21]. Another study from the same group later paired unpleasant odors (US) with cigarette odors (CS) during sleep or wake. They observed a decrease in the number of cigarettes smoked after conditioning in N2 and REM sleep, but not in the control groups, with a more pronounced and long-lasting reduction for N2 sleep. These results suggest that conditioning during sleep can modify behavior for at least several days [19].

Conditioning was also tested in two studies on newborns. They found that coupling a tone (CS) to an air puff to the eye (US) led the sleeping newborns to have a four-fold increased eye movement response (CR) compared to before learning [17]. A similar effect was not observed in the control group, which was considerably smaller than the experimental group. The second study replicated these findings in both NREM and REM sleep [20], with a stronger effect in NREM sleep. Together, these results suggest that conditioning during sleep is possible in newborns, but it is still unclear if this transfers to wakefulness.

3.1. Perceptual and statistical learning

Perceptual learning refers to the enhancement of the ability to recognize, categorize, and discriminate sensory stimuli through repeated exposure [22], while statistical learning involves identifying patterns or statistical regularities between elements received as sensory input [23]. Overall, eight studies—comprising one multiple-case study and seven pre-, quasi-, or experimental studies—were conducted on perceptual and statistical learning between 1966 and 2022 [24–31], six of which objectively verified sleep using EEG and scored sleep systematically (Table 3, and for comprehensive details, see Table S4).

All three studies investigating perceptual learning during sleep, found it to be effective [24,25,28]. Participants in a multiple-case study were able to discriminate two different tones in NREM sleep [24]. Participants in another study learned segments of white noise during sleep, with higher accuracy and shorter reaction times during wake for stimuli presented in wake and REM sleep, but impaired performance for stimuli presented in NREM sleep [28]. However, analyzing the neural data, EEG markers of perceptual learning, such as standard auditory potentials, were observed for both REM and light NREM trials upon awakening, and the suppressive effect was only present for N3 trials. Lastly, a study demonstrated that newborns are also capable of distinguishing similar

Table 2
Studies on conditioning during sleep 1965–2020.

Study Authors Year	Participants	Design (D) Objective (O)	Stimuli (S = CS | US) Presentation time (PT)	Outcome measures (OM = CR) Measurement time (MT)	Findings	Effectiveness
Beh and Barret 1965 [15]	20 healthy adults (Exp = 10, control = 10)	**D:** Experimental pre-/post- between-groups comparison **O:** Study sleep conditioning, extinction, and discrimination	**S:** Tone | Finger shock **PT:** Sleep (stage C)	**OM:** Desynchronization of alpha rhythm (in wakefulness) & k-complexes (in sleep) **MT:** Sleep & wakefulness	Higher CR% to CS in experimental vs control groups (no CS-US); decreased alpha rhythm for CS in wakefulness; CS response extinction in stage C	+
Ikeda and Morotomi 1996 [16]	5 healthy adults	**D:** Quasi-experimental pre-/post- within-groups comparison **O:** Compare conditioning in different sleep stages & transfer to wake	**S:** Tone | Leg shock **PT:** Sleep (S2 & SWS)	**OM:** HR **MT:** Sleep & wakefulness	Higher CR% to CS in experimental night vs control nights (random CS-US) only in SWS; positive correlation between S2 CR and wake CR (learning transfer)	+
Fifer et al., 2010 [17]	30 newborns (Exp = 26, Control = 4)	**D:** Experimental pre-/post-between-groups comparison **O:** Study conditioning in sleeping newborns	**S:** Tone | Airpuff to the eye **PT:** Sleep	**OM:** Eye movement **MT:** Sleep	4× increase in CR to CS for experimental group; no increase in control (random CS-US)	+
Arzi et al., 2012 [18]	65 healthy adults (Exp = 55, Control = 10)	**D:** Quasi-experimental pre-/post- between-groups comparison **O:** Study the effect of odor pleasantness on sleep/wake CR rate	**S:** Tone | Pleasant/unpleasant odors **PT:** Sleep (REM & NREM)	**OM:** Sniff response **MT:** Sleep & wakefulness	Successful CS-US pairing in REM & NREM; significant difference in CR% to CSs; transfer to wakefulness only from NREM conditioning	+
Arzi et al. 2014 [19]	66 smoking quitters (Exp = 34, Control = 32)	**D:** Experimental pre-/post- between-groups comparison **O:** Test impact of sleep-based implicit learning on behavior	**S:** Cigarette odors | Unpleasant odors **PT:** Sleep (N2 & REM)	**OM:** Cigarette count pre- and post-training **MT:** Wakefulness	CR reduction for conditioning in N2 & REM (stronger for REM/transfer of N2 conditioning); no reduction after conditioning in wakefulness or controls (no SC-Us or different CS)	+
Tarullo et al., 2016 [20]	38 newborns (Exp = 21, Control = 17	**D:** Experimental pre-/post- between-groups comparison **O:** Study the role of sleep states on learning in newborns	**S:** Tone | Airpuff to the eye **PT:** Sleep (active (REM) & quiet (NREM))	**OM:** Eye movement **MT:** Sleep	>2× increase in CR to CS for experimental group; no increase in control (no CS-US); stronger conditioning in NREM	+
Canales-Johnson et al., 2020 [21]	43 healthy adults (REM & NREM = 28, NREM = 15)	**D:** Quasi-experimental pre-/post- between-groups comparison **O:** Uncover the brain activity supporting sleep discriminatory associative learning	**S:** Tone | Pleasant/unpleasant odors **PT:** Sleep (NREM & REM)	**OM:** Sniff response **MT:** Sleep	Delta and sigma activity form new associations early in learning; theta activity emerges later after associations are established	+

"+": effective; "0": not effective; CR: Conditioned response; CS: Conditioned stimulus; D: Design; Exp: Experimental; HRV: Heart rate variability; Hz: Hertz; MT: Measurement time; NREM: Non-rapid eye movement sleep; O: Objective; OM: Outcome measures; S: Stimuli; PT: Presentation time; REM: Rapid eye movement sleep; S: Seconds; US: Unconditioned stimulus.

vowel sounds during sleep by showing an increased amplitude of mismatch negativity to deviant stimuli in the experimental group [25].

Since statistical learning likely plays a significant role in language acquisition, interestingly it has successfully been shown in sleeping infants. Newborns are able to detect word boundaries and learn transitional probabilities during REM sleep [26] and learn the first syllable of words during sleep [30]. A quasi-experimental study involving adults revealed no auditory responses indicative of ongoing statistical learning during NREM sleep, but only in wakefulness [29]. However, two experimental studies found that minor deviations from transitional probabilities were associated with mismatch responses across all sleep stages [27] and enhanced neural entrainment over time [31], indicating the brain's capability to detect basic irregularities during sleep.

4. Procedural learning

Procedural memories are a type of long-term memory involved in the learning and performance of motor skills and habits. Procedural training is not restricted to overt muscle movement execution: the efficacy of using motor imagery as mental training for motor tasks has been demonstrated since the 1970s [32], which engages similar brain regions as actual motor execution both during wakefulness [33] and sleep [34, 35]. Three quasi-experimental and one qualitative study [36–39], carried out between 2010 and 2018, showed that lucid dreaming provides an opportunity for enhancing motor skills during sleep [36–39]. However, only one study verified sleep using EEG and systematically scored sleep stages (Table 4, and for comprehensive details, see Table S5).

Using both a coin tossing and sequential finger-tapping task in a home setting it was shown that participants engaging in lucid dreaming practice show significant improvements though at levels below physical practice [36,37]. A study replicated these findings using a dart-throwing task in a laboratory setting with verified dream lucidity [39]. Analysis of the performance change revealed that lucid dreamers with low distraction rates showed significant improvement. In contrast, the other groups (physical practice, no practice, and lucid dreamers with high distraction rates) did not. A qualitative study conducted semi-structured interviews with lucid dreamers from various countries, revealing that 81% of the participants reported positive effects of lucid dream practice, and 62% reported improvements in physical performance [38]. While all these studies were restricted to the rehearsal of motor skills that had already been acquired before sleep, in principle nothing speaks against the initiation and training of entirely new motor procedures during lucid

Table 3
Studies on perceptual learning during sleep 1966–2022.

Study Authors Year	Participants	Design (D) Objective (O)	Stimuli (S) Presentation time (PT)	Outcome measures (OM) Measurement time (MT)	Findings	Effectiveness
Weinberg 1966 [24]	5 healthy adults	**D:** Multiple-case study **O:** Test discrimination of stimuli in sleep	**S:** Tone **PT:** Sleep (C, D, E)	**OM:** Accumulative response to tones **MT:** Sleep	2/5 displayed discrimination in initial 10 trials, and 3/5 eventually acquired it	+
Cheour et al., 2002 [25]	45 newborns (Exp = 15, Controls = 15 & 15)	**D:** Experimental post-test between-groups comparison **O:** Test discrimination of stimuli in sleep	**S:** Vowel sounds **PT:** Sleep	**OM:** Mismatch negativity (MMN) **MT:** Sleep	Discrimination: significant difference in pre-post MMN only in experimental group	+
Teinonen et al., 2009 [26]	30 newborns	**D:** Pre-experimental post-test within-groups comparison **O:** Test statistical learning in sleep	**S:** 3-syllable pseudo-words in random syllable stream **PT:** Sleep (active (REM))	**OM:** ERP responses **MT:** Sleep	Significant difference between ERPs elicited by the first and third syllables	+
Strauss et al., 2015 [27]	31 healthy adults	**D:** Experimental post-test within-group comparison **O:** Test detection of novelties at different levels in sleep and if it relies on prior waking exposure	**S:** Standard and deviant sets of vowels Local (single-vowel change) and (whole-sequence change) **PT:** Sleep & wake	**OM:** Mismatch negativity (MMN), mismatch response (MMR) & ERP responses **MT:** Sleep & wake	Significant difference between the MMR of local standards and deviants in all sleep stages; No response (P300) to the global deviants in sleep.	+
Andrillon et al., 2017 [28]	20 healthy adults	**D:** Experimental post-test within-groups comparison **O:** Test perceptual learning across sleep stages	**S:** Repeated white noise segments **PT:** Sleep (N2, N3 & REM) & wakefulness	**OM:** Behavioral efficacy (sensitivity + reaction time) **MT:** Sleep & wakefulness	Facilitative for REM learning & suppressive for N3 learning; positive correlation: perceptual learning and tonic REM/slow spindles in N2; negative correlation: perceptual learning & slow waves in N3.	+
Farthouat et al., 2018 [29]	21 healthy adults (>5 min exposure = 11, <5 min exposure = 10)	**D:** Quasi-experimental post-test between-groups comparison **O:** Test statistical learning in sleep	**S:** Statistical and random auditory streams **PT:** Sleep (NREM) & wakefulness	**OM:** Recognition scores + MEG frequency-tagged responses **MT:** Sleep & wakefulness	No frequency-tagged responses in both groups; no significant difference between recognition scores of two groups	0
Flo et al., 2022 [30]	24 newborns	**D:** Quasi-experimental post-test within-groups comparison **O:** Test statistical learning in sleep	**S:** Semi-random concatenation of 3-syllable pseudo-words **PT:** Sleep	**OM:** ERP responses **MT:** Sleep	Significant difference between ERPs following the correct first syllables and wrong ones; no significant difference with subsequent violations in transition probabilities	+
Batterink & Zhang 2022 [31]	32 healthy adults	**D:** Experimental post-test between- and within-groups comparison **O:** Test statistical learning in sleep	**S:** Artificial disyllabic and trisyllabic word streams **PT:** Sleep (N3) & wake	**OM:** Behavioral and ERP responses **MT:** Sleep and wake	Enhanced neural entrainment observed for disyllabic words over time; no corresponding behavioral impact	+

"+": effective; "0": not effective; D: Design; Exp: Experimental; Hz: Hertz; MEG: Magnetoencephalography; MMN: Mismatch negativity; MT: Measurement time; NREM: Non-rapid eye movement sleep; O: Objective; OM: Outcome measures; S: Stimuli; PT: Presentation time; REM: Rapid eye movement sleep; S: Seconds.

Table 4
Studies on procedural learning during sleep 2010–2018.

Study Authors Year	Participants	Design (D) Objective (O)	Stimuli (S) Presentation time (PT)	Outcome measures (OM) Measurement time (MT)	Findings	Effectiveness
Erlacher & Schredl 2010 [36]	26 healthy adults (LDP = 6, PP = 10, Control = 10)	**D:** Quasi-experimental pre-/post-between-groups comparison **O:** Compare motor learning in lucid dreams to other practices	**S:** None **PT:** Lucid REM	**OM:** Pre vs. post aiming task performance difference **MT:** Wakefulness	Significant improvement: Physical practice > lucid dreaming	+
Stumbrys et al., 2016 [37]	64 healthy adults (LDP = 17, MP = 15, PP = 16, Control = 16)	**D:** Quasi-experimental pre-/post-between-groups comparison **O:** Compare motor learning in lucid dreams to other practices	**S:** None **PT:** Lucid REM	**OM:** Pre vs. post aiming task performance difference **MT:** Wakefulness	Significant improvement in all groups, except control group	+
Schädlich et al., 2017 [39]	27 healthy adults (LDP = 9, PP = 9, Control = 9)	**D:** Quasi-experimental pre-/post-between-groups comparison **O:** Compare motor learning in lucid dreams to other practices	**S:** None **PT:** Lucid REM	**OM:** Pre vs. post dart throwing task performance difference **MT:** Wakefulness	Significant improvement only in lucid dreamers with low distraction rate	+
Schädlich & Erlacher 2018 [38]	16 healthy adults with frequent lucid dreams	**D:** Qualitative **O:** Gain in-depth understanding of the benefits and applications of lucid dreaming practice in sports	**S:** None **PT:** Lucid REM	**OM:** Answers in the semi-structured Interviews **MT:** Wakefulness	81% reported positive effects of lucid dream practice; 62% reported improved physical performance.	+

"+": effective; "0": not effective; D: Design; Exp: Experimental; Hz: Hertz; LDP: Lucid dreaming practice; MP: Mental practice; MT: Measurement time; NREM: Non-rapid eye movement sleep; O: Objective; OM: Outcome Measures; PP: Physical practice; PT: Presentation time; REM: Rapid eye movement sleep; S: Seconds.

Table 5
Studies on verbal learning during sleep 1942–2022.

Study Authors Year	Participants	Design (D) Objective (O)	Stimuli (S) Presentation time (PT)	Outcome measures (OM) Measurement time (MT)	Findings	Effectiveness
Leshan 1942 [40]	40 nail-biter children (Exp = 20, Control = 20)	**D:** Quasi-experimental post-test between groups comparison **O:** Test whether sleep learning can stop nail-biting habit	**S:** Negative suggestion about nail-biting **PT:** Sleep	**OM:** Outcome of the visual examination (bitten or unbitten fingernails) **MT:** Wakefulness, every two weeks	Stopping nail-biting in experimental group but not the control group	+
Leuba and Batemen 1952 [41]	1 healthy adult	**D:** Case study **O:** Test whether participant could remember the information she was exposed to during sleep in wake	**S:** 3 Songs of different lengths **PT:** Sleep	**OM:** Free recall scores **MT:** Wakefulness	Participant recalled 2 songs perfectly and made 3 errors in 3rd.	+
Fox and Robbin 1952 [42]	30 healthy adults (Facilitation = 10, Interference = 10, Control = 10)	**D:** Experimental pre-/post- between-groups comparison **O:** Examine the influence of sleep learning on relearning during wakefulness	**S:** Chinese-English word pairs **PT:** Sleep	**OM:** Number of trials required for successful learning **MT:** Wakefulness	Facilitation group relearned faster than other groups in wakefulness.	+
Simon and Emmons 1956 [43]	85 healthy adults with IQ > average (Exp = 21, Control = 64)	**D:** Quasi-experimental post-test between-groups comparison **O:** Test the immediate response and later recall of stimuli during sleep-wake continuum	**S:** General knowledge questions and answers **PT:** Sleep (all stages except REM) & wakefulness	**OM:** Recognition scores **MT:** Wakefulness	No significant difference in item recognition between groups; higher recognition accuracy in experimental group for wakefulness and drowsiness stimuli	0
Emmons and Simon 1956 [44]	122 healthy adults (Exp = 9, Control = 113)	**D:** Quasi-experimental post-test between- and within-groups comparison **O:** Test if repetitive training has an effect on learning during sleep	**S:** One-syllable nouns **PT:** Alpha-free sleep	**OM:** Recognition scores **MT:** Wakefulness	Significant difference in item recognition between groups for items followed by alpha but weren't heard; no significant difference in item recognition between groups; no significant difference between trained list and untrained list in experimental group	0
COBB et al., 1965 [45]	8 healthy adults (high hypnotizability = 4, Low hypnotizability = 4)	**D:** Quasi-experimental post-test within- and between-groups comparison **O:** Evaluate behavioral responsiveness to verbal suggestions during sleep	**S:** Suggestions and cue words **PT:** Sleep	**OM:** Correct responses to cues and free recall scores **MT:** Sleep and wakefulness	Correct responses to cues in REM (high hypnotizability only); no transfer to wakefulness	+
Evans et al., 1966, 1969, 1970 [46–48]	18 healthy adults with high/low hypnotizability	**D:** Quasi-experimental post-test & follow up. **O:** Evaluate behavioral responsiveness to verbal suggestions during sleep	**S:** Suggestions and cue words **PT:** Sleep (stage 1)	**OM:** Behavioral responses to suggestions and Free recall scores **MT:** Sleep & wakefulness	Number of participants with correct responses tested in different times: 11/18 in the same REM period, 6/18 in the subsequent REM, 7/18 in the second night REM, 5/7 in the REM after 5 months; no transfer to wakefulness	+
Tani and Yoshii 1970 [49]	103 healthy adults (Exp = 43, Control = 60)	**D:** Quasi-experimental post-test between- and within-groups comparison **O:** Clarify the relationship between sleep EEG patterns and the effectiveness of sleep-learning	**S:** Unrelated word pairs **PT:** Sleep (Light, deep & REM sleep)	**OM:** Free recall scores **MT:** Wakefulness	Significant difference between groups and lists only when stimulation followed by alpha waves	0
Bruce et al., 1970 [50]	21 healthy adults (Facilitation = 7, Interference = 7, Control = 7)	**D:** Experimental pre-/post-between-groups comparison **O:** Examine the influence of sleep learning on relearning during wakefulness	**S:** Nonsense word pairs **PT:** Sleep (Stage C, D & E)	**OM:** Number of trials required for successful learning **MT:** Wakefulness	Relearning in wakefulness: no significant difference between groups	0
Metcalf 1972 [51]	40 hospitalized adult alcoholic patients (Exp = 20, Control = 20)	D: Experimental pre-/post-between-groups comparison O: Assess the efficacy of sleep-learning therapy in treating alcoholism	**S:** General positive suggestions **PT:** Sleep	**OM:** Questionaries on well-being **MT:** Wakefulness	Well-being improvement: no significant differences between experimental and control groups	0
Cooper and Hoskovec 1972 [52]	11 highly hypnotically susceptible adults	**D:** Experimental post-test within-groups comparison **O:** Test if learning with hypnosis lead to recall in wake.	**S:** Russian-English word pairs **PT:** Sleep (REM) & wakefulness	**OM:** Free recall and recognition scores **MT:** Wakefulness	90% free recall of materials presented in wakefulness; 30% free recall of materials presented in REM sleep	+
Levy et al., 1972 [53]	10 healthy teenagers	**D:** Pre-experimental repeated measures **O:** Test if training over multiple nights leads to better learning	**S:** Russian-English word pairs **PT:** Sleep (Stage 4 & REM)	**OM:** Free recall and recognition scores **MT:** Wakefulness	No free or cued recall; recognition scores better than chance (=zero); better recall of new material over nights	+

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Table 5 (*continued*)

Study Authors Year	Participants	Design (D) Objective (O)	Stimuli (S) Presentation time (PT)	Outcome measures (OM) Measurement time (MT)	Findings	Effectiveness
Lasaga & Lasaga 1973 [54]	28 healthy adults (Exp = 8, Control = 20)	**D:** Experimental post-test within-groups comparison **O:** Test perception of verbal stimuli across sleep stages	**S:** Numbers **PT:** Sleep (N2, N3, N4 & REM)	**OM:** Free recall and recognition scores **MT:** Wakefulness	Significant difference between trained (experimental) and untrained (control used as chance level) groups in recall and recognition scores	+
Lehmann & Koukkou 1974 [55]	27 healthy adults	**D:** Correlational **O:** Test the relationship between quality of learning and stimuli-induced EEG activations	**S:** Novel and familiar sentences **PT:** Sleep (SWS)	**OM:** Free recall and recognition scores **MT:** Wakefulness	Significant positive correlation between stimuli-induced alpha (frequency & duration) and recall + recognition scores; novel stimuli induced more alpha activity than familiar stimuli for the same quality of learning	+
Shimizu et al., 1977 [56]	51 healthy adults	**D:** Experimental post-test within-groups comparison **O:** Study the retention duration of stimulation during sleep and the effect of succeeding sleep stage and stimuli modality on it.	**S:** Names and photic stimuli **PT:** Sleep (S2 & REM)	**OM:** Free recall scores **MT:** Wakefulness	Free recall only when stimulation followed by alpha; no effect of stimuli modality; positive correlation between retention period and duration of stimuli-induced alpha activity; no significant effect of following sleep stage on recall	0
Perry et al. 1978 [57]	10 healthy students with high/low hypnotizability	**D:** Quasi-experimental post-test within-groups comparison **O:** behavioral responsiveness to verbal suggestions/cues during sleep	**S:** Suggestions and cue/dummy words **PT:** Sleep (REM)	**OM:** Behavioral response, free recall, and skin potential response **MT:** Sleep & wakefulness	Correct responses only to cue words and not dummy words; no significant relationship between sleep responsivity and hypnotic susceptibility.	+
Bierman and Winter 1989 [58]	12 healthy adults	**D:** Pre-experimental post-test within-groups comparison **O:** Test the effect of repetition on learning during sleep	**S:** Unrelated word pairs **PT:** Sleep (late Stage2)	**OM:** Recognition scores **MT:** Wakefulness	Above chance level (=25) performance for pairs that elicited alpha in late stage 2; no effect of repetition	0
Wood et al., 1992 [59]	22 healthy adults (Exp = 10, Control = 12)	**D:** Experimental post-test between- and within- groups comparison **O:** Test Implicit recall of material presented in sleep	**S:** Word pairs **PT:** Sleep (S2 & REM) & wakefulness	**OM:** Free recall, recognition, and priming scores **MT:** Wakefulness	Significant difference between presented and unpresented lists in wake but not sleep group; significant difference between sleep and wake group in memory tests	0
Cox et al., 2014 [60]	12 healthy adults	**D:** Experimental post-test within-groups comparison **O:** Explore neural and behavioral indices of long-term memory formation during sleep.	**S:** Sounds of real-world objects **PT:** Sleep (N3)	**OM:** Recognition scores and ERP measures **MT:** Wakefulness	No significant difference in novel vs. presented stimuli in memory test; enhanced late ERP response for presented stimuli during sleep up-states; no significant difference in wake ERPs for novel vs. presented stimuli	0
Ruch et al., 2014 [61]	16 healthy adults	**D:** Correlational **O:** Study word encoding during sleep, their priming during wake, and their relationship with presentation time	**S:** Two-syllable words **PT:** Sleep (NREM)	**OM:** Semantic and perceptual priming scores **MT:** Wakefulness	Below-chance performance in priming tests of words presented during sleep; positive correlation between priming scores and the magnitude of word-evoked up-states	0
Andrillon and Kouider 2016 [62]	17 moderately sleep deprived adults	**D:** Experimental post-test within-groups comparison **O:** Investigate forming memories and related neural signatures during sleep	**S:** Words **PT:** Sleep (NREM) & wakefulness	**OM:** Recognition and confidence scores **MT:** Wakefulness	No significant differences between the recognition scores of new and presented words; higher confidence scores for NREM words compared to new words	+
Züst et al., 2019 [63]	41 healthy adults	**D:** Experimental post-test within-groups comparison **O:** Investigate the implicit recall of verbal items presented during sleep and the effect of presentation time on recall level	**S:** Word and pseudoword pairs **PT:** Sleep (NREM)	**OM:** Priming scores **MT:** Wakefulness	Significant above chance level performance in recall performance; higher chance of recall when stimulation coincided with SWS up-states	+
Konkoly et al., 2021 [64]	36 healthy adults, narcoleptic adults, or frequent lucid dreamers	**D:** Multiple-case study **O:** Test two-way communication between dreamers and experimenters	**S:** Auditory, visual, and tactile stimuli **PT:** Sleep (Lucid REM)	**OM:** Free recall scores **MT:** Wakefulness	Successful recall of the question and answers in lucid REM	+
Koroma et al., 2022 [65]	22 healthy adults	**D:** Experimental post-test within-groups comparison **O:** Investigate forming new associations during sleep, their transfer to other domains, and related neural signatures during sleep	**S:** Japanese word-sound-picture pairs **PT:** Sleep (REM & NREM) & wakefulness (in another control experiment)	**OM:** Recognition and confidence scores **MT:** Wakefulness	Significant above chance level performance in recall performance for NREM pairs; no significant difference in confidence scores of NREM lists vs control lists and correctly remembered items vs errors	+

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Table 5 (*continued*)

Study Authors Year	Participants	Design (D) Objective (O)	Stimuli (S) Presentation time (PT)	Outcome measures (OM) Measurement time (MT)	Findings	Effectiveness
Schmidig et al., 2022 [66]	30 healthy adults	**D:** Experimental post-test between- and within-groups comparison **O:** To test the encoding and storage of word pairs, the effect of presentation time on recall, and recall time	**S:** Foreign-German word pairs **PT:** Sleep (NREM)	**OM:** Recognition, categorization, and confidence scores **MT:** Wakefulness	Overall retrieval: above-chance level but not significant; feeling heard and confidence: no significant difference between correct and incorrect responses; presentation and retrieval time: higher retrieval accuracy for trough-targeted pairs compared to peak-targeted pairs/trough-targeted pairs recall significantly exceeded chance only at 36 h	+

"+": effective; "0": not effective; D: Design; EEG: Electroencephalography; Exp: Experimental; Hz: Hertz; MT: Measurement time; NREM: Non-rapid eye movement sleep; O: Objective; OM: Outcome measures; S: Stimuli; PT: Presentation time; REM: Rapid eye movement sleep; S: Seconds.

dreaming, thus potentially enabling de-novo motor learning during sleep.

5. Verbal learning

While efforts of non-verbal learning during sleep have shown some promise, most sleep learning research has focused on verbal learning, e.g., hoping to acquire language without conscious effort. Among the twenty-seven studies conducted between 1942 and 2022 [40–66], encompassing case studies, pre-, quasi, and experimental designs, twenty-three verified sleep using EEG and systematically scored sleep stages (Table 5, and for comprehensive details, see Table S6).

The earliest studies were inspired by the belief that individuals are more receptive to suggestions during sleep, similar to hypnosis. They aimed to determine the impact of playing positive or negative suggestions during sleep on wake behavior, with contradictory findings, such that a study from 1942 found that nail-biting ceased after repeated exposure to the suggestion “My fingernails taste terribly bitter” while a study conducted thirty years later found no effect of positive suggestions during sleep over eight months on well-being [40,51]. Since then, no studies have attempted to use suggestions during sleep to influence waking habits, however, a newer study has used conditioning to influence waking habits (see conditioning section).

A series of studies conducted between 1965 and 1978 aimed to examine suggestibility during sleep by testing participants’ behavioral responses while using EEG to confirm sleep [45–48,57]. Results from a pilot study showed that only highly hypnotizable participants who heard suggestions during REM sleep correctly carried out the instructed behavior within 30 s of subsequently hearing the cue word during REM sleep [45]. A subsequent study that included a larger sample size, two experimental nights, and a five-month follow-up reported that at least some participants could correctly act upon suggestions in REM sleep not only during the same night, but also the following night, and even several months later [46–48]. However, due to the absence of a proper control and/or comparison group in this study, it is difficult to definitively attribute the observed effects solely to sleep learning rather than potential influences from other variables. A last study showed that these responses were specific to the suggestion sentence, as responses were only elicited by the relevant cue words and not irrelevant dummy words. None of the mentioned studies found any sign of retaining explicit or implicit memories of verbal stimulation during sleep in ensuing wakefulness [57].

The above studies show that the sleeping brain possesses the capacity to process stimuli and form sleep-specific memories. These memories appear to be uniquely accessible during sleep and hold the potential to alter wake behavior. However, it is still unclear whether new information acquired during sleep, such as learning a new language, can transfer to the waking state. The first experiment on the possibility of learning verbal material during sleep and recalling it in wakefulness was a case study conducted in 1952 [41]. The study reported the participant was able to recall songs played during sleep with a high degree of accuracy the following day. However, the absence of sleep verification and the lack of learning reported by the participant after using and subsequently discontinuing insomnia medication left a lot of questions unanswered.

In the following years, several experimental investigations tested verbal learning during sleep. Two studies investigated the potential benefits of presenting language material during sleep to enhance subsequent learning during wakefulness, but with diverging results with the first study demonstrating faster learning after previous exposure during sleep, but the second study not finding any benefit of NREM sleep learning [42,50].

Some studies have used free recall or multiple-choice recognition tests upon waking to measure the transfer of verbal learning from sleep to wake, showing a 30% recall rate for word pairs from REM sleep compared to a 90% recall rate from wake [52] with recognition scores only marginally better than chance even after five training nights [53]. Notably, hypnosis was used to induce sleep in both studies. Moreover, the first study involved highly hypnotizable participants, and the second study’s credibility is limited due to the absence of a proper control or comparison group.

Along with behavioral measures such as free recall and recognition tests, several studies also examined brain activity during sleep. Novel general questions and answers presented during sleep did not lead to a better performance when recognizing answers [43], and even with repeated exposure, one-syllable nouns were not recognized significantly more the following morning [44]. Both studies reported that stimuli were only recalled later if an arousal (alpha activity) co-occurred. However, the control groups in both studies exhibited variations in sample size and testing conditions compared to the experimental groups. These variations introduce potential confounding factors that compromise the internal validity of the studies, emphasizing the need for a cautious interpretation of their statistical outcomes. Nonetheless, several other studies have found similar results. Short-term memory of numbers tended to decrease from stage 1 and REM to SWS [54], and sentences presented during deep NREM sleep followed by longer durations of alpha activity measured in posterior regions resulted in better learning outcomes compared to shorter durations of alpha activity measured in the same region [55]. Similarly, presenting names during REM and NREM2 sleep [56], unrelated words during all stages of sleep [49], and multiple lists of unrelated word pairs during NREM light sleep [58] resulted in successful recall only when the stimulus elicited alpha activity.

Previous studies investigating verbal learning during sleep have primarily focused on explicit memory retrieval, which involves conscious recall and recognition of the learned information. More recent research has employed novel methods to explore the possibility of

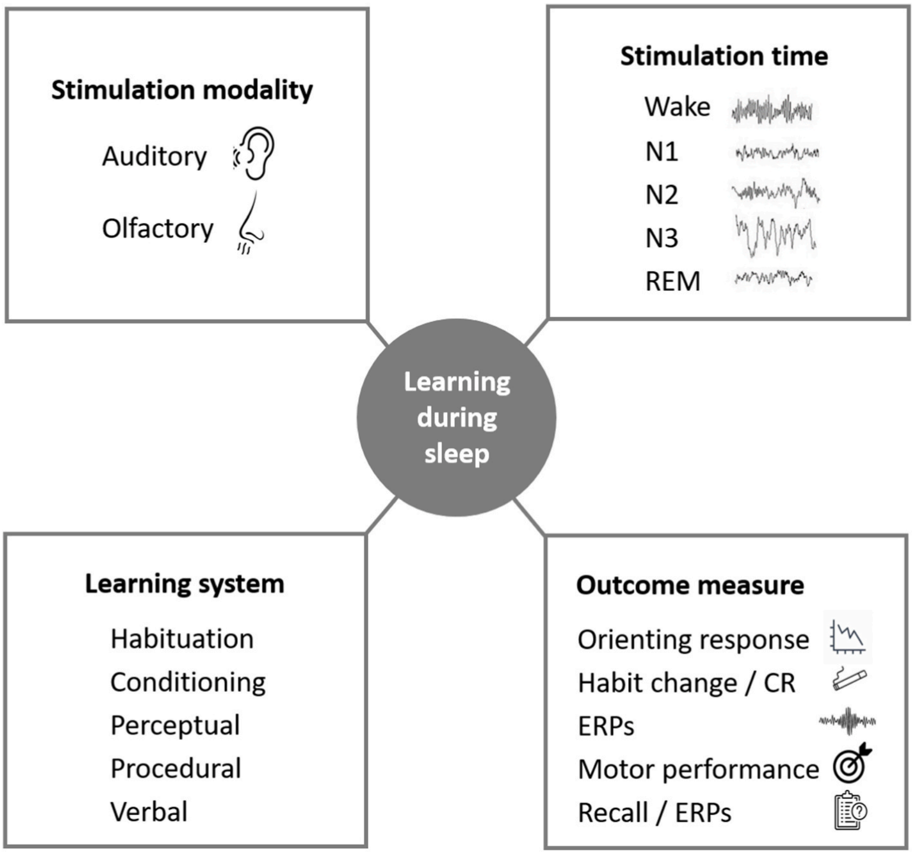

Fig. 2. Methodology and design overview of sleep-learning studies. CR: Conditioned response; ERPs: Event-related potentials; REM: Rapid eye movement sleep.

implicit memory retrieval, which involves the unconscious recall of learned information. In addition to usual recall and recognition tasks, one study employed priming tasks to evaluate the implicit retrieval of word pairs—homophones paired with their close associates (e.g., hare-tortoise) and categories paired with their instances (e.g., metal-gold)—which were repeatedly presented during wake or sleep [59]. While participants in the awake group demonstrated significantly better performance in all tasks for presented items than for non-presented items, those in the REM and light NREM sleep group did not. Another study employed a confidence score to explore the implicit and explicit encoding of verbal memory during sleep and wakefulness, showing that words presented during wakefulness are well-remembered with both high recognition and accuracy scores [62]. In contrast, the words presented during NREM sleep were not remembered or recognized, suggesting an absence of explicit memory. However, comparing confidence ratings of sleep-presented items to new ones showed a higher confidence when labeling sleep-presented items as old and a lower confidence when labeling them as new, implying that participants were more certain in recognizing sleep-presented items as familiar. Additionally, ERP analysis uncovered distinct processing patterns for sleep-presented items when being heard during wakefulness, distinguishing them from new items. These outcomes hint at the presence of implicit memories linked to sleep-presented items, even if not statistically significant at the behavioral level.

In addition to using implicit measures of memory retrieval, a promising recent trend is optimizing stimulus presentation timing to increase the likelihood of learning. The first study that adopted this approach presented two-syllable German words rhythmically during NREM deep sleep to elicit slow wave oscillations that are believed to be crucial for consolidating memory [61]. However, their participants performed at chance level in both the perceptual and semantic priming tests, indicating no explicit or implicit memory of the sleep words. Still, a positive correlation was found between the scores in the priming tests and the magnitude of word-evoked up-states, which suggests a possible role of slow-wave up-states in verbal encoding during sleep. A subsequent study employed a novel algorithm to present real-world sounds during slow-wave up- and down-states [60]. The researchers discovered no significant differences between sleep-presented items (in either slow-wave up- or down-state) and novel items in performance levels in a recognition task or in brain responses during wakefulness. However, subsequent to the presentation of stimuli during sleep, they observed evoked potentials consistent with standard auditory evoked potentials, implying some degree of processing embedded in the memory trace of the stimuli. Additionally, the up-state-targeted stimuli resulted in larger K-complexes than the down-state-targeted stimuli. In another study, participants were shown word-pseudoword pairs during slow-wave sleep, where the word represented an object [63]. Upon awakening, they were tested to see if they could recall whether the object associated with the pseudoword could fit inside a shoebox, measuring implicit recall. The results indicated that the participants' performance was above chance level, with the majority of learning occurring when the presentation of the second word coincided with the second evoked up-state during intervals of decreased theta power measured in frontal regions. Furthermore, the behavioral data from this study was reanalyzed in another study [67], which probed the carry-over effects of sleep learning to wakeful learning. Counterintuitively, the results showed that sleep learning impairs the subsequent awake learning of the same associations. A different study, however, showed opposing results [66]. The participants were presented with foreign words and their translations simultaneously in slow-wave up- and down-states. Only the down-state targeted word pairs exhibited significantly better performance in a categorization retrieval task conducted 36 hours after sleep learning. Confidence scores displayed no significant difference between correct and incorrect answers, indicating no explicit retention of the auditory stimulation. Moreover, enhanced frontal theta activity measured post-stimulation significantly correlated with retrieval accuracy. Another study showed that information learned during sleep could be retrieved implicitly and cross-modally when awake [65]. The study found that participants performed above-chance in the recognition task for NREM words but not for REM or new words. Based on their analysis of the confidence scores, the researchers suggested that memories formed during sleep were implicit, whereas memories formed during wakefulness were explicit. In addition, evoked slow-wave frontal activity during sleep predicted memory performance in wake.

Based on the evidence provided by the aforementioned studies, one could infer that explicitly recalling verbal material presented during sleep may not be possible, even when the chance of encoding is increased by adjusting the timing of stimulus presentation. However, a recent study has shown that it is possible to form explicit episodic memories during sleep under certain circumstances [64]. The study used auditory, visual, and tactile stimuli to communicate with participants experiencing lucid dreams during REM sleep. Upon awakening, the participants were able to recall the specific questions asked, indicating that in this particular state of sleep, encoding relatively complex episodic memories of external stimuli is possible.

6. Discussion

Several studies have been conducted to investigate the effectiveness of both verbal and non-verbal learning during sleep in humans. A summary of their design and methodology is shown in Fig. 2. Non-verbal implicit learning during sleep has shown some promise, with certain studies demonstrating the transfer of learning to wakefulness. Further, recent studies have identified behavioral and neural markers of implicit verbal learning during sleep. In contrast, the explicit recall of materials learned during sleep seems to be impossible in most cases, with a notable exception being a study where stimuli were incorporated into lucid dreams during REM sleep [64]. To fully comprehend the implications of these findings and conduct rigorous research on verbal learning during sleep, it is necessary to carefully consider the similarities, differences, and interconnections between implicit and explicit memory systems, both at neural and behavioral levels [68].

Several studies have demonstrated that the human brain can process semantic information during sleep [69–73] and even use it to prepare task-relevant responses [74]. However, it is possible that the limitations of the sleeping brain in encoding semantic stimuli at the same level as wakefulness make the recall difficult. Neuroimaging studies have demonstrated that the presentation of stimuli during sleep activates similar areas in the brain as during wakefulness, including both cortical and subcortical regions, although at a lower level for the prefrontal cortex and the thalamus [71,72]. Moreover, the amplitude and latency of ERPs [73] are unfavorably affected during sleep, indicating deficits in neural representation. These findings may explain the significant differences in learning observed between sleep and wakefulness for the same verbal materials [43,52,59,62,65]. However, it is important to note that the lower stimulus intensity levels used in sleep learning studies, which are required due to the lower auditory threshold for arousal during sleep, may have also negatively impacted the encoding of stimuli.

Another reason why verbal learning is less successful than conditioning and habituation during sleep might be the stimulus type. While olfactory stimuli used in conditioning and habituation are processed in subcortical regions and are less likely to cause awakenings [75], verbal learning involves complex auditory stimuli that require processing in the cortex and are more likely to cause arousal [71,76], reducing its effectiveness during sleep.

Indeed, several studies conducted between 1956 and 1989 tried to clarify if learning truly happened during sleep or if some wakefulness or arousal (measured by the presence of alpha activity) is necessary. These studies highlight a crucial issue: a certain level of arousal is necessary for effective learning to occur during sleep. However, the criteria used to define arousal, such as the duration of alpha activity, varied widely across these and more recent studies that have excluded arousals and still observed effective learning. Additionally, it has been suggested that while longer REM-alpha arousals (complete arousals) involving changes in muscle activity can disrupt sleep, shorter REM-alpha bursts (micro-arousals) may facilitate the brain’s connection with the external environment during sleep without generating a significant shift in brain state [77]. Therefore, different stimuli-driven arousals must be distinguished to determine if they disrupt the natural sleep or have only a minor impact that justifies the attempt to learn while asleep. For practical applications, micro-arousals that do not influence sleep quality might be well tolerated, especially if they enable sleep learning.

Interestingly, if we look at the overall trends regardless of learning modality, it appears that there is more evidence for learning during NREM sleep compared to REM sleep, particularly when looking at the transfer to wakefulness. Successful learning during sleep has been associated with slow-wave activity, a hallmark of NREM sleep [60,61,63,65]. However, in responding to verbal cues while asleep [45–48,57] and conditioning effects during sleep [18], REM sleep seems more promising than NREM sleep. The stronger transfer from NREM learning to wakefulness may be linked to the observed increased functional connectivity between olfactory and neocortical areas during slow-wave activity [78] for the studies that used olfactory stimulation, but this does not explain the results from other stimuli modalities. Considering that NREM sleep also appears to be more involved in memory consolidation, it could be hypothesized that memory consolidation interferes with the acquisition of new memories or vice versa. A recent meta-analysis conducted on the relationship between learning before sleep and memory performance tested after sleep showed a robust and statistically significant correlation between the incorporation of a task into NREM dreams (but not REM dreams) and memory performance [79], however, no study has directly investigated how sleep learning influences the consolidation of previously acquired memory.

The greater plasticity of young brains may lend itself to learning under circumstances that would be non-optimal or prohibitive later in development [80]. For example, immature organization of sleep states may be permissive to neonatal learning during sleep. Newborns’ sleep states are poorly defined and become more organized over the first two years of life [81]. Infants also differ from adults in their resting state networks during sleep, and it is thought that the default-mode network observed in adults may emerge gradually as the brain develops [82]. Perhaps the opportunity for learning in non-awake states diminishes as sleep patterns mature throughout development. This aligns with the finding that all infant studies found the presence of sleep learning, however, only non-verbal learning can be used in infancy. Several age ranges, including preschool and old age, have not been studied. Especially school age, when humans acquire the most declarative knowledge and would probably enjoy using a “hypnobioscope” the most, may be particularly interesting.

The reviewed studies have several methodological and design limitations (Refer to Tables S2, S3, S4, S5, and S6 for comprehensive details on stimuli parameters, post-stimuli events, sleep verification measures, sleep type, and sleep scoring). While a few of the studies examined the potential for enhancing learning during sleep by adjusting stimuli parameters, such as the number of repetitions, drawing definitive conclusions about the optimal stimuli parameters is challenging due to the numerous design and methodological limitations involved. Moreover, early studies often did not specify the sleep verification method, relied solely on behavioral monitoring, or did not specify which rules were applied to score sleep. In addition, some studies induced sleep through pharmacological and hypnotic methods, which could have influenced the quality and quantity of sleep. Lastly, the majority of studies had small sample sizes, limiting their statistical reliability and generalizability. Nonetheless, these studies provided some indications for subsequent studies to build upon.

Practice points

1. The studies reviewed on learning during sleep exhibited substantial variability in methodology, aims, and design. This variance led to contradictory findings, underscoring the need to meticulously evaluate the particulars of each study when interpreting the results.
2. Studies have consistently shown promising results for habituation, conditioning, and perceptual learning during sleep. Conditioning, in particular, has demonstrated the potential for practical applications.
3. Some studies found no learning of verbal material during sleep or null or negative effects on relearning the same material. However, by modifying stimuli presentation time, novel verbal material presented during sleep was retrievable during wakefulness implicitly or explicitly when presented in lucid REM sleep.

Research agenda

1. Prioritize improving the accuracy of sleep verification and scoring, controlling for relevant variables, and refining the experimental design to reach more reliable results, e.g., utilizing more sensitive and appropriate measures of implicit and explicit verbal learning, such as standardized tests.
2. Develop suitable methods and tasks to evaluate implicit verbal learning during sleep and examine how implicit memory acquired during sleep influences explicit memory during wakefulness.
3. Compare wake learning and sleep learning of both verbal and non-verbal material to identify the types of learning that are more promising during sleep and might lead to practical applications.
4. Investigate the impact of sleep learning on the ongoing consolidation of information learned during wakefulness.
5. Optimize stimulation properties during sleep, such as changing modality, intensity, the complexity of stimuli, and presentation methods and timing to enhance the processing and encoding of stimuli.
6. Conduct longitudinal studies to determine the long-term benefits of sleep learning.
7. Examine whether incorporating stimuli into dreams enhances memory performance in wakefulness.

7. Conclusion

The highly varied methodologies and designs in studies on learning during sleep present a challenge in reaching definitive conclusions. Nonetheless, while explicit retrieval of information presented during sleep may not easily be accessible while awake, behavioral and neurophysiological evidence suggests that implicit retrieval of verbal and non-verbal information is possible. To further advance our understanding, future research should compare learning during sleep and wakefulness using consistent methodologies while optimizing methods and conditions such as presentation time (during SWS or lucid REM) and stimuli properties. Additionally, investigating the potential influence of lucid dreaming on learning during sleep could yield valuable insights into this fascinating area of research. For the time being, it appears that developing a “hypnobioscope” is still a long way off from becoming a reality.

Declaration of competing interest

The authors declare that there are no conflicts of interest concerning this work.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.smrv.2023.101852.

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