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Influencing dreams through sensory stimulation: A systematic review

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ABSTRACT

Sleep is typically considered a state of disconnection from the environment, yet instances of external sensory stimuli influencing dreams have been reported for centuries. Explaining this phenomenon could provide valuable insight into dreams' generative and functional mechanisms, the factors that promote sleep continuity, and the processes that underlie conscious awareness. Moreover, harnessing sensory stimuli for dream engineering could benefit individuals suffering from dream-related alterations. This PRISMA-compliant systematic review assessed the current evidence concerning the influence of sensory stimulation on sleep mentation. We included 51 publications, of which 21 focused on auditory stimulation, ten on somatosensory stimulation, eight on olfactory stimulation, four on visual stimulation, two on vestibular stimulation, and one on multimodal stimulation. Furthermore, nine references explored conditioned associative stimulation: six focused on targeted memory reactivation protocols and three on targeted lucid reactivation protocols. The reported frequency of stimulus-dependent dream changes across studies ranged from 0 to ~80%, likely reflecting a considerable heterogeneity of definitions and methodological approaches. Our findings highlight a lack of comprehensive understanding of the mechanisms, functions, and neurophysiological correlates of stimulus-dependent dream changes. We suggest that a paradigm shift is required for meaningful progress in this field.

1. Introduction

Dreams—those spontaneous, internally generated conscious experiences that emerge while we sleep—have sparked our curiosity since the dawn of humanity. However, despite being a prevalent component of our daily (or rather nightly) lives, dreams are still poorly understood. Contrary to the long-held belief that dreaming is exclusive to rapid eye movement (REM) sleep, it is now clear that conscious subjective experiences ranging from simple abstract thoughts to complex movie-like narratives occupy a significant portion of our nights [1,2]. Extensive sampling over multiple nights and different sleep stages revealed that the memory of having dreamt accompanies more than 70% of awakenings from sleep; nevertheless, individuals may be unable to recall any specific content in up to 40% of cases [3]. Therefore, if humans spend about one-third of their lives sleeping, they must also dream for at least one-fifth of their lives. This estimate is already reason enough to drive scientific interest towards dream neurophysiology, yet it is hardly the only one. The occurrence and content of dreams are also intricately related to the dreamers' mental and physical health [4,5]. Changes in dream frequency or content are commonly reported symptoms of primary sleep disorders, including insomnia and parasomnias, and psychiatric and neurologic diseases such as post-traumatic stress disorder (PTSD), anxiety disorder, narcolepsy, or Parkinson's disease [6]. However, studying dreams and their alterations objectively and reproducibly is difficult due to their highly subjective nature and large variability across and within individuals [7].

These considerations have piqued the scientific community's interest in approaches that may arbitrarily and systematically influence the features of dream experiences [8]. Such 'dream engineering' approaches could significantly advance basic and translational research. For instance, they could allow for empirical investigation into the biological functions of dreaming via direct manipulations of oneiric features and even counteract dream alterations associated with pathological conditions [9]. Yet, while several dream engineering approaches have been scientifically tested, ranging from pre-sleep experience manipulation to sensory or brain stimulation procedures [8], their precise physiological and phenomenological effects remain largely unknown.

Among the available dream engineering techniques, sensory stimulation protocols seem particularly promising. In fact, while sleep is known to involve some degree of sensory disconnection from the external environment [10], dream modifications caused by sensory

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Glossary

Alpha activity *Neural oscillations in the frequency range of 8–12 Hz, predominantly occipital, typically observed during closed-eye resting wakefulness*

Arousal threshold *The intensity of a stimulus necessary to induce a behavioural response or awakening from sleep.*

Bottom-up *Cognitive or perceptual mechanism in which information is processed starting from sensory input and gradually building up to more complex, higher-level cognitive representations*

Chemosensory *Detection and interpretation of environmental chemical stimuli, namely taste and smell*

Dream engineering *Methods and technologies aimed at influencing and arbitrarily modifying dream experiences to improve sleep, mental well-being, or cognitive processes*

Exposure therapy *Therapeutical technique for the psychological treatment of fear-related issues, based on exposure to the fear-inducing stimulus in a safe environment*

K-complex *EEG waveform (0.5-2 Hz) comprising an initial positive bump, followed by a giant negative deflection and a large positive one. The K-complex represents the expression of widespread, synchronised neuronal silencing (off-period). They can occur spontaneously or in response to sensory stimuli*

Lucid dreaming *Dreaming state in which the dreamer is aware of being asleep and dreaming*

Nociception *Detection and processing of noxious or painful stimuli*

Non-rapid eye movement (NREM) sleep *Sleep stage characterised by lower-frequency EEG activity and the absence of rapid eye movements, as opposed to REM sleep. It comprises N1, N2, and N3 sleep.*

N1 sleep *First and lightest stage of sleep, often considered as a transitional state from wakefulness to sleep, First and lightest stage of sleep characterised by a slowing of the EEG activity and slow rolling eye movements. Conscious and perceptual experiences may accompany it, sometimes called hypnagogic hallucinations*

N2 sleep *Predominant sleep stage, characterised by low-frequency, large-amplitude EEG activity, and by the occurrence of K-complexes, slow waves, and spindles*

N3 sleep *Deepest stage of sleep characterised by very low frequencies and high amplitude EEG activity, also known as 'slow-wave sleep.'*

Mechanoreception *Type of somatosensory perception aimed at detecting mechanical stimuli, such as pressure, touch, or vibration*

Microarousal *Abrupt shift in EEG frequency, including alpha activity and/or frequencies greater than 16 Hz (excluding the spindle band), typically lasting between 3 and 15 s*

Conditioned association *Type of learning related to the classical conditioning effect, in which an individual associates two stimuli or events, allowing one to serve as a cue to the other*

Reality-testing techniques *Set of techniques based on the experiential examination of the surroundings, often used to induce lucid dreams by triggering awareness of any inconsistencies or oddities in the dream environment, distinguishing the dream from reality*

Rapid eye movement (REM) sleep *Sleep stage characterised by a wake-like EEG activity, rapid eye movements, and muscular atonia. Dream reports accompany most awakenings from this stage*

Serial-awakening procedure *Experimental sleep session involving multiple awakenings with experiential probing*

Slow wave *EEG negative-to-positive wave (0.5-4 Hz) reflecting a slow oscillation in membrane potential at the neuronal level, characterised by an alternation between a hyperpolarised "silent" phase (off-period) and a depolarised phase of intense firing activity (on-period)*

Somatosensory *Sensory system responsible for perceiving and processing various bodily sensations, including touch, pressure, temperature, pain, and proprioception*

Spindle *Transient waxing-and-waning 10–16 Hz EEG oscillation generated in the thalamus as a result of interactions between inhibitory, GABAergic neurons of the thalamic reticular nucleus and thalamocortical, glutamatergic relay cells*

Thermoception *Type of somatosensory perception specialised in the perception of temperature*

Trigeminal *Relating to or involving the trigeminal nerve, which plays a crucial role in various sensory functions, including touch, temperature, and pain perception*

Vestibular *Sensory system providing information about the body's position and motion, which is crucial for balance, spatial orientation, and movement coordination*

Abbreviations

EEG	Electroencephalography
NREM	Non-rapid eye movement
PRISMA	Preferred reporting items for systematic reviews and meta-analyses
PTSD	Post-traumatic stress disorder
REM	Rapid eye movement
SDDC	Stimulus-dependent dream change
TMR	Targeted memory reactivation
TLR	Targeted lucidity reactivation
tACS	Transcranial alternating current stimulation
tDCS	Transcranial direct current stimulation
TMS	Transcranial magnetic stimulation

perceptions have been documented and even sought after by philosophers, artists, and scientists alike for centuries [11] (see Supplementary Text S1). Nonetheless, a consensus has yet to be reached regarding the underlying mechanisms and functional significance of stimulus-dependent dream changes (SDDCs), defined here as any change in dream features induced by an external stimulus. Crucially, advancing our understanding of how external stimuli affect dreams may provide new insights into the physiological mechanisms that ensure sleep continuity in the presence of external disturbances and the functional underpinnings of perceptual awareness at different

Therefore, we aimed to summarise and evaluate the available evidence about the effects of experimental sensory stimulation during sleep on ongoing mental activity. We described previous findings about SDDCs and evaluated the feasibility and effectiveness of sensory stimulation approaches for dream engineering. All findings were assessed for potential methodological and statistical limitations. Finally, we addressed open issues and suggested a roadmap for future investigations.

2. Methods

2.1. Identification of publications

This systematic review was conducted following the preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines [12,13]. Four online databases (PsycNET, PubMed, ScienceDirect, and Scopus) were searched for publications investigating the effects of sensory stimuli administered during sleep on dream characteristics. The search query was *'dream* AND (stimul* OR sensory OR modulat*)'*, with slight variations depending on specific search engine parameters (Supplementary Table S1). The literature search was first conducted on February 1, 2021, and then again on October 15, 2022. All resulting articles were screened using the inclusion criteria outlined below. Furthermore, bibliographic references from the selected papers were recursively checked for potential inclusion.

2.2. Inclusion criteria

One author (LS) conducted a three-step evaluation process to select publications. First, off-topic publications were excluded based on their title. Then, the abstracts of all remaining articles were assessed to evaluate their potential compliance with a set of pre-selection criteria (Supplementary Table S2). We pre-selected all published or in-press research articles in English that included an experimental stimulation protocol during sleep targeting at least one of the following sensory modalities: visual, auditory, olfactory, gustatory, vestibular, or somatosensory, with the latter encompassing touch, thermal perception, nociception, and proprioception. We included any article that reported sensory stimulation effects on dreaming, even when this was not the study's primary goal. Instead, we excluded articles focusing only on neuromodulation or brain stimulation techniques, namely transcranial direct or alternating current stimulation (tDCS/tACS) and transcranial magnetic stimulation (TMS). This type of stimulation aims to bypass canonical information processing pathways by modulating neuronal oscillatory activity directly and thus differs substantially from pure sensory stimulation techniques. Although a sensory component may somehow be present (e.g., somatosensory perceptions due to electrical stimulation), its effect cannot be distinguished from the direct neuromodulatory effects of the procedure. We also excluded articles that relied on drug administration.

Finally, pre-selected articles were narrowed down based on finer exclusion criteria (Supplementary Table S3). We discarded studies for which we could not retrieve the full manuscript. Publications that did not use a standard sleep monitoring technique (i.e., EEG or actigraphy) were excluded since participants' vigilance state might not have been adequately confirmed. We also excluded single-case studies and non-experimental publications, such as anecdotal reports and observational studies, as well as research involving hypnotic states or post-hypnotic conscious experiences. We further excluded papers that failed to provide any quantitative or qualitative information about the collected dream reports (i.e., studies that claimed to have gathered dream data without reporting it). Articles that lacked any methodological details about the stimulation procedure were also discarded. In the same vein, we excluded publications that reported multiple manipulations without properly separating the resulting data, as this prevented the identification of any specific effects of the different stimulation techniques.

Finally, we focused our review on non-lucid dream data since lucid dreaming is often regarded as a distinct state of sleep consciousness. In fact, lucid dreams are characterised by different patterns of brain activity relative to ordinary dreaming and present unique qualitative features, namely the recovery of metacognition [14]. Nonetheless, we evaluated lucid-dreaming publications for prospective findings about SDDCs in non-lucid dreams. We thus excluded articles that solely reported on the effects of sensory stimulation on lucid dream induction or content, as well as those that pooled lucid and non-lucid dreaming data. A second reviewer (GB) approved of the final selection.

2.3. Data extraction

A meta-analysis was not possible within this systematic review due to the broad differences concerning the metrics and methods adopted by the selected articles. Therefore, results were qualitatively synthesised by one author (LS) using textual descriptions and recapitulative tables. A second author (GB) verified the extracted data and discussed with the first author any disagreements, namely in cases of missing or unclear data.

2.4. Methodological assessment

We assessed the empirical validity and bias risk of all selected publications using a partially modified version of the Downs and Black checklist [15], which was originally developed for evaluating the methodological quality of randomised and non-randomised studies of health care interventions. The adapted checklist comprises 23 items and assesses several methodological aspects, including result reporting, external and internal validity, and statistical aspects, including power and effect size calculations (Supplementary Text S2). The final scores range from 0 to 25.

Two authors (LS, GB) independently scored the studies using this checklist. A consensus was reached after discussing any grading differences. Of note, the checklist was applied to evaluate the reported dream data and dream-related results specifically, even when these were not the focus of the study.

3. Results

3.1. Selected publications

The literature search yielded 51 publications (Fig. 1). Out of these, 21 reported data related to auditory stimulation, 10 to somatosensory stimulation, eight to olfactory stimulation, two to vestibular stimulation, four to visual stimulation, and one to multimodal (audio-visual) stimulation (Fig. 2). Moreover, nine studies involved conditioned associative stimulation procedures: six used targeted memory reactivation (TMR) protocols, and three applied targeted lucidity reactivation (TLR) protocols.

In summary, the selected studies were characterised by high heterogeneity regarding experimental protocols and methodologies, both across and within sensory modalities. In particular, the timing of stimulation and the targeted sleep stage showed substantial variability. Out of the selected studies, 25 targeted only REM sleep, two focused solely on NREM sleep (N1–N2 and N3) [16,17], and the remaining 24 stimulated both during REM and NREM sleep (mainly N2). Six studies were performed during a daytime nap [16,18–22]. Moreover, while most studies involved serial-awakening procedures, five articles used whole-night stimulation protocols, collecting data only once upon spontaneous morning awakening [23–27]. Finally, most studies monitored sleep using EEG, with only two relying on actigraphy measures [23,26]. The sections below briefly describe the selected studies (see also Supplementary Tables S4–S17 for an overview of the methodological details and summarised results of each included publication).

3.2. Methodological assessment

Overall, the included studies obtained a mean score of 13 (13.25 ± 4.48; range 1–22) out of a maximum possible score of 25, indicating the existence of significant methodological limitations. The item-by-item and total scores reflecting the methodological quality of each article based on our checklist are provided in Supplementary Table S18, while the score distribution for each checklist item is shown in Supplementary Fig. S1.

Altogether, study results were typically based on a limited number of observations, with an average sample size of 17.43 ± 15.51 participants (range 3–65) and a small number of collected reports per participant. In this regard, it should be emphasised that both sample size and the number of observations play an essential role in determining statistical power [28]. Additionally, several publications merely reported descriptive findings, with around 30% of the assessed studies failing to provide statistical analyses.

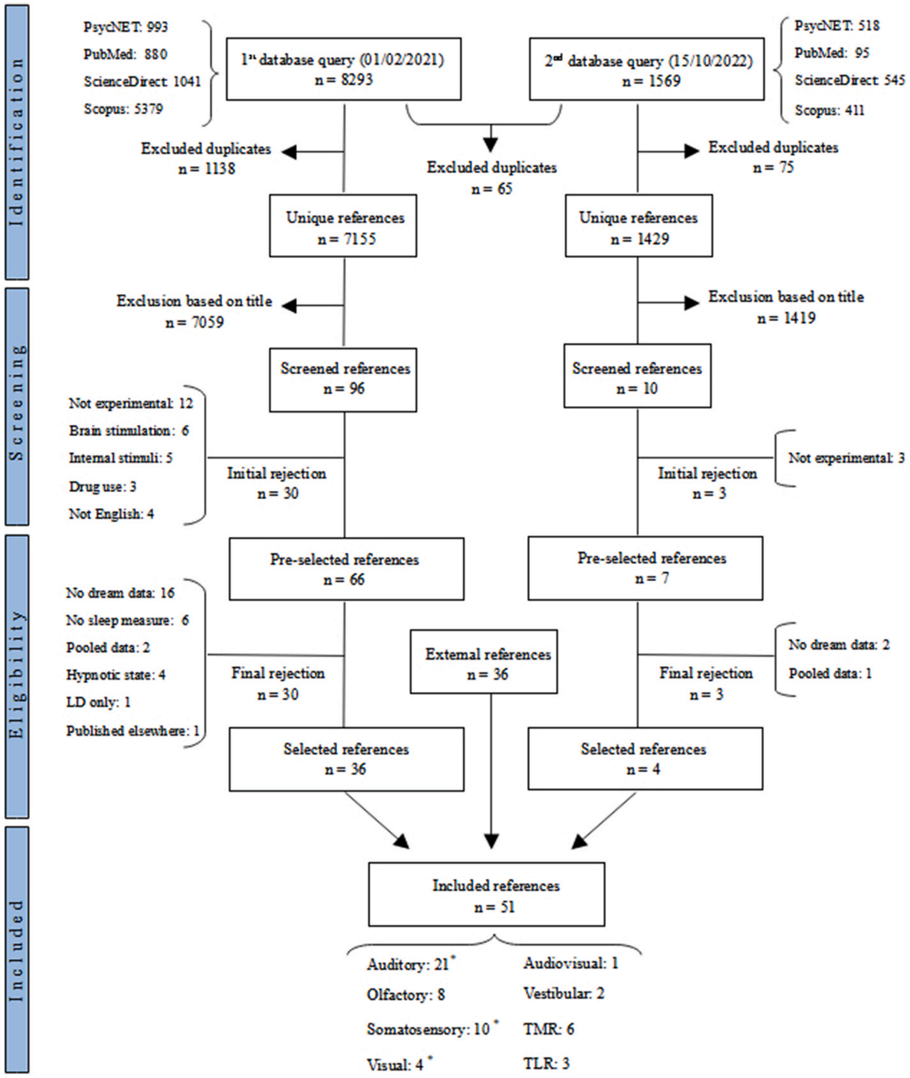

Fig. 1. PRISMA-compliant article selection flowchart.
* This modality was evaluated in a publication that studied more than one modality independently, justifying that the total count across all modalities is higher than the total number of references.
Abbreviations. TMR: targeted memory reactivation; TLR: targeted lucidity reactivation.

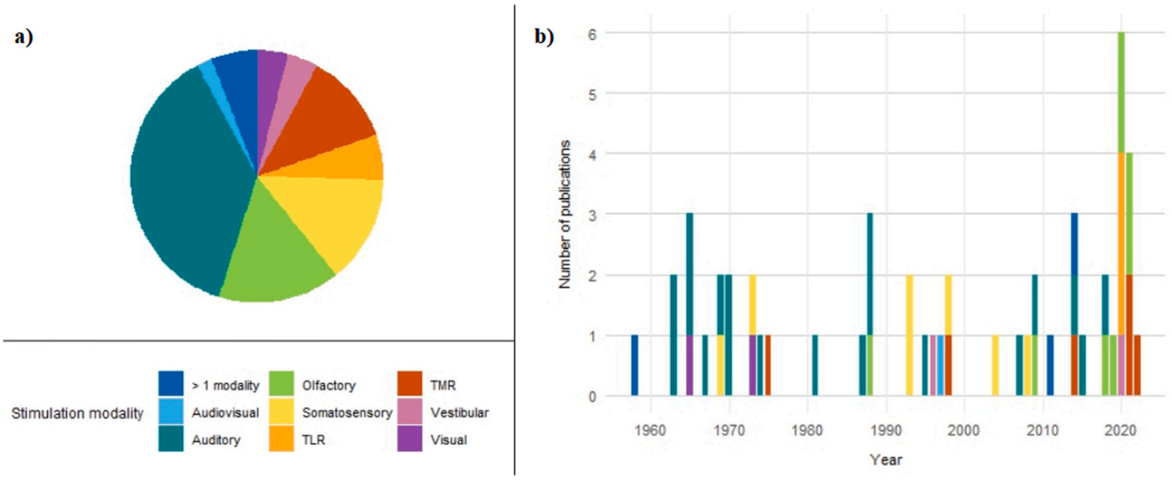

Fig. 2. Distribution of selected studies as a function of the targeted sensory modality (a) and year of publication (b).
Note. Three articles [38,47,56] evaluate more than one modality independently.
Abbreviations. TMR: targeted memory reactivation; TLR: targeted lucidity reactivation.

Other significant issues are the implementation of protocols without any adequate control conditions and the absence of effective blinding measures. Some investigations, for example, made the conditions explicit to the participants or proceeded without randomising the stimulation schemes. Further, investigations relied on human raters to evaluate the occurrence of SDDCs, even though they were not always adequately blinded to the aims of the experiments. Crucially, most studies failed to provide clear definitions and guidelines for identifying SDDCs. Lastly, several studies include poor or misleading statistical reporting, such as across-sample data aggregation procedures. Indeed, rather than focusing on within-subject analyses, about 80% of the evaluated studies pooled data across participants, neglecting individual variance. Most analysed studies did not include power calculations, and many failed to report exact p-values and effect sizes.

The methodological quality of the publications shows a positive trend over time, as evidenced by a significant positive correlation between methodological scores and the year of publication ($r = 0.45$, $p = 0.001$; see Fig. 3), but there is still room for improvement, and future efforts should focus on addressing these limitations.

3.3. *Evidence of SDDCs*

Most reviewed studies focused on specific SDDC types, yet only a few described the adopted SDDC definitions and identification criteria. Based on these, we proceeded to classify SDDCs into two main categories: *incorporation*, which encompasses all instances in which the stimulus permeates the dream content as an identifiable element (i.e., the presence of a novel dream element that presents overlapping characteristics with the stimulus), and *modulation*, which includes all SDDCs that appear to be contingent on the stimulus's presence but cannot be explained by its intrinsic qualities (i.e., variations in general dream features, such as emotional valence or number of dream characters). Whenever possible, depending on the availability of finer categorisation provided by the authors themselves or by the presence of detailed information about the dream content, incorporations were further distinguished as either being *direct* (whenever the stimulus is incorporated as is; e.g., a flashing light is incorporated as light in the dream) or *indirect* (whenever the stimulus is incorporated in a transformed way, namely through semantic or mnemonic associations; e.g., white noise may be incorporated as the sound of waves or as a visual representation of the ocean; Fig. 4). Otherwise, the terminology was kept as used by the authors in the corresponding publication.

3.3.1. *Auditory stimulation*

Auditory stimulation was first implemented in the 1960s and remains the most targeted modality to this day. Indeed, over one-third of the articles selected for this review concerned auditory stimulation (N = 21; ~41%). Studies within this category may be classified into two types, which we summarised separately: those that employed sounds associated with semantic information, such as words or certain identifiable sounds (52%) [16,18,29–37] and those that used non-semantic stimuli, such as pure tones or white noise (48%) [38–47].

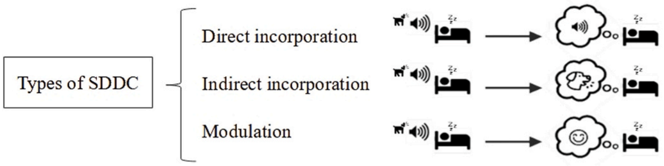

Fig. 4. Schematic representation of the main types of stimulus-dependent dream changes identified in the present review.

Of note, one study [38] used both auditory and somatosensory stimulation independently and is described in the somatosensory stimulation section. Another study used multimodal stimulation (auditory and visual) [48] and is described within this section due to its close relatedness with a series of similar studies based on unimodal auditory stimulation.

3.3.1.1. Semantic stimuli. These studies used verbal stimuli (i.e., spoken words or phrases), non-verbal vocalisations, or recognisable sounds (e.g., traffic noise) to influence ongoing sleep mentation. For instance, some authors explored the degree to which different simple verbal prompts could trigger the occurrence of semantically related elements within the dream. Tilley, Luke, and Boehle [37] used sets of thematically connected words as stimuli and reported finding instances of 'representational relationship' in a third of the collected dream reports, with a higher incidence in REM (8/18) than in N2 reports (2/12) [37]. In another study, a specific word was presented immediately after sleep onset during a daytime nap [16]. All six participants reported 'seeing' the prompted word while dreaming.

Other researchers focused on non-verbal auditory stimuli associated with semantic information. For example, Bruck and Horasan examined the effects of fire alarms on sleep arousal to evaluate the safety of these devices [30]. Stimulus incorporation was detected in ~17% of the participant's dream reports. In another study, traffic sounds were played during REM sleep [35]. There were more thematically related categories ('travel' and 'streets'; [49]) after stimulation (~24%) than in non-stimulated dreams (~4%). Four direct incorporation instances were identified across the 26 dream reports collected during the stimulation night.

A series of studies explored whether variations in the saliency or emotional valence of the stimulus could impact the occurrence of SDDCs by using stimuli such as personally relevant names [29], concern-related

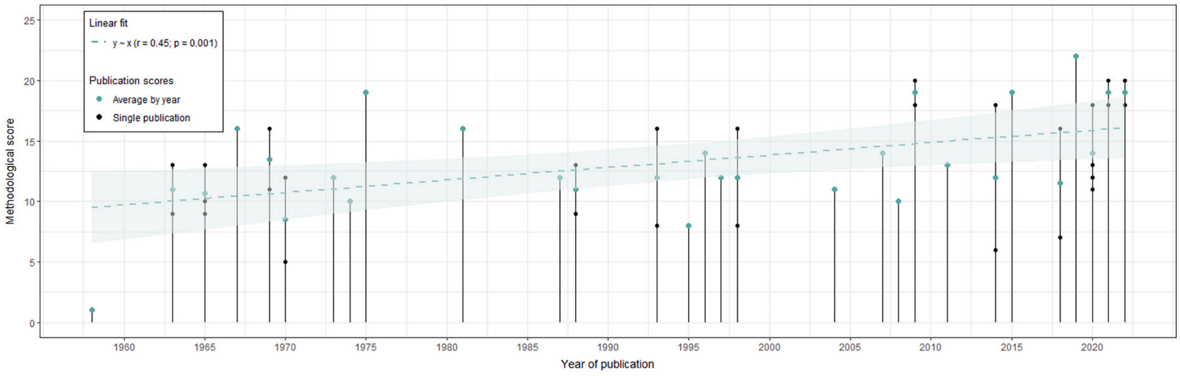

Fig. 3. Methodological score evolution across publication years for selected references.
Note. The green dashed line is fitted to the average methodological score for each year; the light green shadow represents the standard error. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

words [34], or human cries [36]. Hoelscher and collaborators showed that, in REM reports, the incorporation rate of concern-related stimuli was significantly higher than for non-concern-related stimuli. When comparing REM and N2, incorporation rates were higher in REM reports [34]. Similarly, Strauch observed higher incorporation rates in REM reports for the meaningful stimulus (the sound of a crying person) but not for the neutral stimulus (the sound of a jet plane), compared to the control condition [36]. Moreover, when comparing incorporation rates between stimulated waking and sleeping mentation, direct incorporation was more common than indirect incorporation during wakefulness, while the opposite was true for REM sleep.

Others tried to evaluate how linguistic aspects, such as voice ownership or language comprehension, were related to SDDCs. Castaldo and collaborators performed a series of studies in which they presented a set of words recorded either with the dreamer's own voice or a stranger's voice [31–33]. Results showed that the main dream character was more active, assertive, and independent when participants heard their own voice, while the dreamer or main figure was more passive when a stranger's voice was played. Dream reports collected after stimulation also included more listening activities than non-stimulated dreams. The authors further evaluated both direct ('phonological') and indirect ('conceptual') incorporations of the stimuli: when comparing experimental to control awakenings, reports from N2 (but not from REM) showed a greater number of words conceptually related to the stimuli. Instead, Bloxham and Durrant investigated language comprehension by presenting phrases in either English or German to monolingual anglophones [18]. While all collected dream reports contained speech or conversational activities, those following German stimulation tended to be scored as stranger and more unfamiliar, showing a potential modulation effect. Only two reports were rated as possibly incorporating the stimulus.

3.3.1.2. Non-semantic stimuli. The employed stimuli included pure tones (800 Hz–1000 Hz), bell rings, and white noise. Interestingly, the only publication that compared different stimulation modalities found that pure tones had the lowest incorporation rate (9%) compared to visual (23%) and somatosensory (42%) stimuli [47].

Most studies in this category used sensory stimulation to investigate the relationship between induced arousal and ongoing conscious mentation. For instance, a series of works by Shapiro and colleagues investigated the effect of the mode of awakening (gradual or abrupt) on subsequently reported conscious experiences [42–44], showing that gradually increasing the stimulus volume until awakening led to more thought-like reports than abrupt awakenings. When groups of low and high dream recallers were compared, the difference between awakening modes in the tendency to yield thought-like reports was more pronounced for the former. An interaction between the time of night and the method of awakening was also found, with effects being more significant in later REM periods for low recallers specifically. Consistent with this, the authors found an interaction between the sleep stage (NREM or REM) and the method of awakening, depending on the type of report. The authors mention the occurrence of incorporations in both dream-like and thought-like REM reports, although no distinction was made between stimulus-related and laboratory incorporations. Interestingly, the time between the last phasic REM period and awakening was longer for thought-like reports with incorporation than those without incorporation; conversely, for dream-like reports, incorporation instances were closer to the last phasic event.

Along similar lines, a few studies focused on the relationship between arousal thresholds and stimulus incorporation [39,46]. Zimmerman compared the effects of increasingly loud pure tones on light and deep sleepers by stimulating early REM and subsequent N3 stages [46]. He found no clear differences in incorporation rates between light and deep sleepers. Instead, Bradley and Meddis assessed variations of the arousal threshold at the individual level, showing that dream reports containing incorporations (43%) were associated with higher auditory arousal thresholds than those without [39].

Burton and colleagues used beeping tones to investigate changes in responsiveness to external stimuli during sleep [40]. Specifically, participants were stimulated during REM and N2 sleep after being instructed to inhale deeply upon stimulus perception. Evidence of stimulus incorporation (e.g., direct, related to noise, or indirect, related to breathing) was found in 50.8% of REM and 37% of N2 reports, with no significant difference between stages. Behavioural responsiveness to the tones also appeared to be similar for REM and N2. However, it was significantly reduced for trials followed by a dream report, which held true even when only N2 trials were considered. Interestingly, the likelihood of responsiveness was lower in trials with incorporation (50%) than in trials without incorporation (79%), with no difference between sleep stages. In fact, the level of responsiveness for trials where there was no evidence of incorporation was as high as when no dream report was collected.

In a series of three studies, Conduit and colleagues explored how arousal signs and eye movements relate to oneiric experiences [41,45,48]. Two studies employed virtually identical experimental paradigms, although one used multimodal stimulation combining a pure tone with a red pulsing light [48], while the other applied the pure tone alone [41]. The procedures involved repeatedly presenting the stimuli either in N2 or late REM, progressively increasing the intensity until ocular activity was observed. Stimulation in N2 sleep was associated with higher dream imagery scores and more alpha activity relative to the condition without stimulation. No differences were observed between stimulated and non-stimulated trials regarding the amount of visual imagery in REM dreams. Direct incorporation of the stimuli was observed in both studies: in the multimodal experiment, 33% of REM reports were deemed as have incorporated the stimuli, compared to only 12.5% of N2 reports; in the auditory experiment, incorporation was found in 50% of REM and 11% of N2 reports. A follow-up study focusing specifically on REM noted that stimulated trials were associated with a lower amount and amplitude of eye movements [45]. Compared to control trials, dream reports from stimulated trials contained less visual imagery, presented fewer visualisable words, and received lower imagery scores than the no-stimulation condition.

3.3.2. Somatosensory stimulation

Ten (~20%) studies involved somatosensory stimulation: six focused on nociception [38,47,50–53], one on thermoception [27], and the remaining three on mechanoreception [54–56]. Accordingly, stimulation methods differed substantially between investigations. Only three studies by Nielsen and collaborators used comparable stimuli and approaches. In particular, they used inflatable blood pressure cuffs to stimulate the limbs during REM sleep [51,54,55]. Results from the first study showed that post-stimulation dreams contained more references to both pressure cuffs and leg sensations than unstimulated dreams, with over 80% of reports collected after stimulation containing instances of direct incorporation [54]. In another study, pressure cuffs were inflated until they reached the pain threshold [51]. The authors identified pain incorporation in almost a third of post-stimulation dream reports (13/42), of which 11 explicitly mentioned leg pain and two mentioned pain in a transformed way. Dreams presenting pain incorporation also included strong negative emotions. Of note, the dreamed pain was described as more intense than the actual pain experienced upon awakening, a characteristic that has been mentioned repeatedly for many centuries [57,58] (see also Supplementary Text S1). The last study in this series compared the effect of pressure stimulation on dream activity in gymnasts and non-gymnasts [55]. Overall, post-stimulation reports included stimulus incorporation in nearly half of cases. However, non-gymnasts presented more such references in their dreams than gymnasts. Finally, stimulation was found to be associated with a smaller number of characters in the dream plot, with this modulation effect being mostly driven by the gymnast group.

Five other studies employed distinct types of somatosensory stimuli to induce painful sensations, thus evaluating the effect of nociceptive stimulation on sleep and dreams [38,47,50,52,53]. Dement and Wolpert sprayed cold water on different exposed body parts and found that subsequent dream reports incorporated the stimulus in up to 42% of cases [47]. Koulack applied electrical impulses to the wrists of the participants while varying both the time of stimulation and awakening [53]. Results showed that stimulating shortly after REM detection was more effective in modifying the dream experience than stimulating later in REM or during NREM sleep. Overall, stimulus incorporation was more frequent in stimulated than control trials. Furthermore, certain qualitative aspects of the dream content related to somatosensory perception ('body centrality' and 'body activity') were more frequently identified after stimulation in REM than in NREM or control trials. Interestingly, the author also compared trials containing alpha activity in the EEG signal with trials that did not and found that 'alpha dreams' presented higher incorporation rates than dreams without such arousal signs [53].

The three studies described hereafter were mainly focused on exploring the physiological effects of nociceptive stimulation during sleep, assessing its possible effects on dreams only as a secondary aim. In the first one, hypertonic intramuscular infusions were applied to evaluate nociceptive thresholds across the wake-sleep cycle [52]. Five out of nine participants reported perceiving pain in their sleep, and two reported pain incorporation in their oneiric experiences. In the second study, radiant heat laser pulses were applied overnight [50]. In this case, only four out of ten participants could recall any conscious experience, none presenting any somatosensory or pain incorporation. The third study presented aversive stimuli, either unconditioned (mild electric shocks) or cued (by presenting a negatively conditioned neutral auditory stimulus), both in N2 and REM sleep [38]. Self-reported dream emotionality showed a shift towards higher negative valence ratings after experimental nights compared to unstimulated baseline nights. Importantly, these three studies collected dream-related details only after morning awakening. This implies variable and potentially long temporal intervals relative to when the stimulation occurred, which could contribute to the lack of clear effects.

The only thermoception-based study included in our review investigated how room temperature influences the type and intensity of emotional content in dreams [27]. Results showed that emotional intensity was significantly lower at higher temperatures (and vice versa). Furthermore, unpleasant feelings tended to be scarcer at higher temperatures, with pleasant dreams appearing more frequently.

The last publication in this section focused on lucid dreaming, while also including data regarding non-lucid experiences [56]. Paul and collaborators administered visual (see corresponding section) or vibrotactile stimuli during REM sleep. Self-rated incorporations were identified in 43% of cases following vibration applied to the index finger and in 48% of cases when stimulation was applied to the wrist or ankle.

3.3.3. *Olfactory stimulation*

Among the selected papers, eight (~16%) targeted olfaction [23–26, 59–62]. Odours have the particularity of being processed differently than other sensory stimuli since olfactory information bypasses the brainstem and thalamic hubs. As a result, pure or mildly trigeminal odorants do not cause arousal or increases in K-complexes during sleep; conversely, they even appear to promote slow-wave and spindle activity [63,64]. Furthermore, direct anatomical projections from the olfactory bulb to the primary olfactory cortex connect to the amygdala and hippocampi, which are known to be involved in emotional and memory processing [65,66]. In line with this, most reviewed studies explored the potential effects of different odour attributes, such as odour pleasantness, on dream emotionality.

Trotter, Dallas, and Verdone presented a series of pleasant and unpleasant scents during REM sleep. They observed that the proportion of dream reports with a positive emotional tone was similar for all trials, indicating that dream emotional ratings were unaffected by odour pleasantness [62]. Stimulus incorporation was found in 27% of pleasant and 11% of unpleasant trials. Later, Schredl and collaborators presented one pleasant and one unpleasant odour, again during REM sleep [61]. Results revealed that the emotional tone changed significantly based on pleasantness, with pleasant trials rated more negatively than unpleasant and control trials. No direct incorporation instances were identified.

Okabe and collaborators further investigated the impact of odour pleasantness using a group-level design accounting for individual differences concerning odour preferences [59]. Participants who liked the odour had more negative dreams after being stimulated than those who disliked it, indicating a significant interaction between the group and stimulation conditions. Again, no cases of direct incorporation were identified, but two post-stimulation reports included elements associated with olfactory perception. Since odour preference has been suggested to be associated with odour familiarity, another study compared groups of people who were either familiar or unfamiliar with the presented odour [60]. The high-familiarity group judged their dreams more negatively after stimulation than in the control condition, while no stimulus-induced changes were observed in the low-familiarity group. Yet, when only unstimulated trials were considered, the high-familiarity group rated their dreams more positively than the low-familiarity group.

More recently, Martinec Nováková and colleagues made their participants sleep one night with a pleasant or unpleasant odour and one without [24,25]. The authors found a significant effect of the stimulation condition on dream emotionality ratings, which seemed modulated by whether participants perceived the odour upon awakening. Specifically, perceiving an odour without stimulation was associated with lower dream pleasantness than accurate rejections. Nonetheless, neither stimulation nor odour appraisal upon awakening seemed to affect the frequency of chemosensory content in dreams. Instead, 'chemosensory dreams' were more commonly reported by participants with a greater propensity to detect and act upon smells in everyday life.

The last two studies in this category focused on the effects of olfactory stimulation on overall sleep quality. Both used actigraphy-based sleep monitoring to evaluate the influence of whole-night stimulation with a pleasant odour on clinical populations suffering from sleep disturbances (i.e., post-traumatic stress disorder [26] and mild to moderate chronic insomnia patients [23]). The first found that emotional intensity ratings were significantly lower for dreams collected after stimulation nights compared to control nights, while no effect was observed regarding emotional tone [26]. The second was home-based, with participants being asked to spray a fragrance on their pillow before bed. Although one of the two tested fragrances was associated with better sleep quality ratings, the results failed to show any effect of odour stimulation on dream content [23].

3.3.4. *Vestibular stimulation*

Two studies (~4%) targeted the vestibular system [20,67]. One was originally aimed at inducing lucidity in dreams [67]. To do so, participants slept in a hammock that started rocking either during early or late REM sleep. Dreams collected from early stimulated REM periods were rated as more self-reflective than unstimulated dreams. Stimulus incorporation was identified in 25% of stimulated dreams and 7% of unstimulated ones. Furthermore, there was a significant correlation between vestibular incorporation and dream bizarreness. The other study explored how different bed inclinations could affect conscious experiences during sleep [20]. Participants reported hypnagogic imagery more frequently after control nap awakenings than after stimulation. However, the amount of vestibular or somatosensory content did not vary as a function of bed elevation.

3.3.5. *Visual stimulation*

Four articles (~8%) involved visual stimulation [17,47,56,68]. In one study, participants slept with their eyes taped open while physical objects were presented before them [68]. No obvious incorporation cases were identified among the 30 collected dream reports, and reports were matched to the corresponding object at the chance level. However, the authors stated that up to four reported experiences might have potentially incorporated the light used to illuminate the presented objects.

In the remaining studies, the stimuli consisted of simple flashing lights that could be perceived through closed eyelids. Using such an approach, Dement & Wolpert identified stimulus incorporation in seven of 30 dream reports [47]. These included, for instance, the report of a sudden fire, lightning, shooting stars, or the experimenter shining a flashlight towards the eyes in the dream scene.

In another study, visual or tactile stimuli were administered during REM sleep to induce lucid dream episodes [56]. Dream reports were collected in 18 out of 24 stimulation trials, of which the participants rated seven (38.9%) as having incorporated the stimulus. Visual stimulation was also used to change the frequency of oscillatory activity in visual areas during sleep. Specifically, photic stimulation flickering at the frequency of the participants' alpha peak (~10 Hz) was used to entrain neural oscillatory activity during N3, under the hypothesis that increasing alpha oscillations would lead to an increase in REM-like sleep mentation [17]. Oscillatory stimulation at 26 Hz was used as a control condition. The percentages of experiences judged as REM-like were 25% in unstimulated N3, 17% after stimulation at 26 Hz, and 93% after alpha stimulation.

3.3.6. *Conditioned association*

In nine selected studies (~18%), the presented stimuli had previously been paired with a task or other stimuli during wakefulness. Such procedures aim to associate a stimulus with some information that may be subsequently reactivated by using the stimulus as a cue. This technique can be used to induce the reactivation of specific memories, as in targeted memory reactivation (TMR) protocols [69], or to induce lucidity within the dream, as in targeted lucidity reactivation (TLR) procedures [70].

3.3.6.1. TMR. While most TMR studies focused on how memory reactivation relates to learning and behavioural performance, six assessed its effects on dream content. Of these, four used auditory cues [21,22,71,72], one used olfactory cues [73], and one used visual cues [19]. Overall, these studies showed inconsistent results regarding the immediate incorporation of the reactivated information.

De Koninck and Koulack asked a group of volunteers to watch a stressful film before sleep; the soundtrack was then played during REM sleep [72]. Film incorporation ratings were significantly higher for dreams collected after the soundtrack was presented, but only for participants who had previously watched the film. Direct incorporation of the audio stimulus reportedly occurred only once. Anxiety ratings of the collected dreams did not differ between stimulated and unstimulated conditions, and no correlation was found between dream anxiety and film incorporations.

In a more recent experiment, participants engaged in a virtual reality flying task before taking a nap, during which task-related audio cues were once again presented [21,22]. Three of the 18 collected REM TMR dreams were rated as incorporating the auditory cue, whereas none of the 17 NREM TMR dream reports were; yet, incorporation was not associated with any improvement in post-sleep task performance [22]. On the other hand, the authors found a significant positive effect of REM TMR on post-sleep task performance, and spontaneous incorporation of kinaesthetic task elements into the content of REM dreams was predictive of greater performance improvement. Interestingly, while TMR cueing had no discernible immediate effects on task-element dream incorporation, an increased incorporation of such elements was found in reports collected with a home dream diary two days after the REM TMR nap or five to six days after the NREM TMR nap [21].

The last auditory-based TMR study attempted to enhance social fear extinction in individuals suffering from social anxiety [71]. A group of patients participated in virtual-reality-based exposure therapy sessions, of which the positive feedback phase was either associated or not with an auditory cue. The following week, cueing was done during home-based REM sleep using a wearable EEG device. For participants in the experimental condition, the change in dream fear between the weeks before and after exposure was positively correlated with anxiety-related distress scores and spontaneous electrodermal activity, as measured at the end of the experimental procedure.

Schredl and colleagues [73] paired images of either urban or rural landscapes with one of two distinct odours, which were then presented again during REM sleep. The presentation of the odour associated with rural pictures seemed to increase the frequency of rural-related dreams, but this effect was not observed for city topics. There was no evidence of stimulus-dependent modulation of the emotional tone of the dreams, and only two dream reports included some reference to smell, one of which was not preceded by any odour stimulation.

Finally, Conduit and Coleman implemented a protocol in which citrus juice, known to induce saliva production, was paired with the flashing of two red lights during wakefulness [19]. The visual cue was then presented in REM sleep during a daytime nap. While salivary excretion rates measured upon awakening were significantly higher after cueing than after unstimulated REM awakenings, none of the 14 collected dreams included any content related to food, hunger, thirst, drinking, or citrus juice (i.e., indirect incorporation). Nonetheless, one-third of stimulated dreams showed signs of direct incorporation of the cue.

3.3.6.2. TLR. Erlacher and collaborators published three TLR studies that included non-lucid dreaming data [74–76]. The first evaluated the effectiveness of associating reality-testing techniques with an odour that would serve as a lucidity cue when presented during REM sleep [74]. Out of 16 participants, only one reported incorporating the stimulus, leading to lucidity.

The remaining studies were based on auditory cueing. Volunteers received specific training in performing reality tests for becoming lucid whenever they heard the cue (either a short phone ringtone [75] or a music track [76]), which was then repeatedly presented during REM sleep. In the first study, 12 out of 40 TLR dream reports were judged as presenting some degree of direct incorporation of the ringtone; in two cases, this also led to lucid dream episodes. Three TLR reports showed potential indirect incorporation (i.e., the appearance of a phone within the dream), and the difference in incorporation rates between control and stimulation nights was significant [75]. In the second study, music as a theme was present in eight out of 38 late REM dreams without there being any differences between stimulated (4/24) and control (4/14) trials [76]. Direct incorporation of the stimulus within a dream unrelated to music led to a lucid dream episode, whereas lucidity was not reached when the stimulus was indirectly incorporated.

An interesting observation from all three studies is that the realisation of being within a dream seems to be more commonly triggered when the stimulus is directly incorporated as an out-of-context element relative to when the stimulus is transformed to fit into the ongoing dream narrative.

4. Discussion

In the following sections, we summarise the main observations reported in the literature regarding the effects of sensory stimuli on dreams and highlight key issues and open questions for future research.

4.1. *Types of SDDCs*

Most studies failed to provide any clear definition of what the authors considered SDDCs. However, cases of stimulus incorporation have been further classified by several authors as either direct or indirect incorporations [29,32,53], although often with different terms. Additionally, some studies have described SDDCs that do not fall into the above categories, which we collectively labelled as dream modulations.

Given the current state of the literature, a specific assessment regarding the comparative incidence and underlying mechanisms of the several types of SDDCs is currently lacking and impossible to achieve. Therefore, future research should consider at least two significant limitations encountered in prior studies. First, experimenters or blind raters can miss indirect incorporations and modulations. Indeed, forms of indirect incorporation based on idiosyncratic memories and beliefs may remain undetected unless the dreamer is directly involved in their identification [29]. Moreover, dream modulations may take various forms, some of which may be difficult to anticipate. Therefore, the possibility of detecting such SDDCs depends on the specific study hypotheses and assumptions. Second, as discussed below, perceptual distortions of the stimuli may affect the ability of raters to identify instances of direct or indirect incorporation of the transformed stimuli.

4.2. *Differences between sensory modalities*

Almost all included studies focused on one sensory modality, limiting the possibility of direct comparisons regarding the impact and efficacy of distinct sensory stimuli in inducing SDDCs. Only one investigation [47] used different sensory stimuli (audio, visual, and somatosensory) within the same experimental protocol, sleep stage (REM), and participant sample. This work reported differences in the effectiveness of distinct sensory stimuli at inducing direct or indirect incorporations, with water spray being the most effective and a pure tone being the least effective. However, the reported data were pooled across participants, and the results remained at the descriptive level. Bearing this limitation in mind, studies on single modalities appear overall consistent with the reported findings. Indeed, somatosensory stimuli were typically reported as relatively effective at inducing SDDCs. In contrast, the success of auditory stimuli appeared to vary significantly depending on the stimulus characteristics, being lower for pure tones and higher for semantically charged stimuli.

It is interesting to note that olfactory stimuli are rarely associated with direct incorporations but tend to influence emotional aspects of oneiric experiences. Only one study [62] reported incorporations for about one-fifth of the presented olfactory stimuli. However, as noted elsewhere [61], the study lacked appropriate control for potential odour appraisal upon awakening and used potentially arousing trigeminal odours. The lack of an EEG arousal response for pure odours has been suggested to explain their low incorporation rate. In contrast, their impact on dreams' emotional tone could reflect the direct connection of the olfactory bulb to the amygdala [61]. Another interpretation is that specific functional mechanisms could prevent odours from appearing in dreams, in line with the meagre rate of spontaneous olfactory experiences observed in dream diaries (~1%) [77]. Studying congenitally blind individuals, who often present a substantial increase in the incidence of chemosensory content in dreams, could provide further insight into this matter [78].

Another interesting observation concerns the incorporation of visual stimuli. Indeed, the direct incorporation of flashing lights appeared to be relatively frequent, with light stimuli frequently being incorporated as a flashing of the entire scene or of specific objects within the dream [79]. On the other hand, visual stimuli rarely seemed to trigger indirect incorporations or direct incorporations of complex stimuli. Since almost all our dreams are predominantly visual [78], this might reflect a competition between ongoing visual experiences and bottom-up visual inputs.

4.3. *Factors influencing SDDCs*

The reported probability for sensory stimuli to induce changes in dream content greatly varied across studies, ranging from ~0% [68] to ~80% [51]. Besides intrinsic differences between sensory modalities and possible experimental differences among studies, several factors have been suggested to contribute to this variability.

4.3.1. *Subjective relevance of the stimulus*

The fact that stimulus relevance may modulate the probability of inducing an SDDC is especially evident for auditory stimuli. Indeed, semantic auditory stimuli bearing particular significance to the sleeper appear to be incorporated more frequently than less relevant sounds, such as pure tones. Similarly, it has been proposed that the higher incorporation rates for somatosensory stimuli compared to other sensory modalities could be attributed to their greater relevance for the sleeping organism, as physically close stimuli may indicate more imminent danger than distant ones [61].

4.3.2. *Stimulus intensity and duration*

The physical properties of a stimulus, such as its intensity or duration, have been suggested to affect its probability of inducing SDDCs [29,31–33,41,48]. Indeed, one study [39] observed a positive association between stimulus intensity and the probability of incorporation during REM sleep. However, since most studies applied a predefined stimulation intensity, this observation requires further validation. The possible impact of stimulus duration or repetition is even less clear. Some authors specifically employed longer or repeated stimuli, suggesting that this could increase the incorporation probability. Nevertheless, stimulus repetition may reduce the relative saliency of the stimulus [80] and thus its ability to induce an SDDC. Unfortunately, studies directly investigating the impact of repeated versus rare stimuli on SDDCs are still lacking.

4.3.3. *Coherence between stimulus and oneiric experience*

Stimulus incorporation often occurs seamlessly within the ongoing dream narrative [29,47,53]. Considering this, several authors suggested that a stimulus might have a greater chance to be incorporated if it somewhat fits—or could be 'transformed' to fit—into the oneiric experience. Indeed, incorporating sensory stimuli as alien, out-of-context elements (e.g., a verbal stimulus directly incorporated as an 'external voiceover') seems less common. In these instances, dreamers may recognise the incoherence of the stimulus to the ongoing dream scenery and thus become aware that they are dreaming. This reasoning suggests two potential implications. On the one hand, identifying and using stimuli that are unlikely to fit into most dreams could increase the probability of inducing lucid dreams. On the other hand, knowing what a person is likely to dream about (e.g., typical or recurring dreams) may help select stimuli that are more (or less) likely to be incorporated.

4.3.4. *Sleep stage and time-of-the-night*

About half of the reviewed articles investigated NREM (usually N2) and REM sleep, but only a few performed directly comparisons across stages. Of these, some reported a higher rate of SDDCs in REM relative to NREM sleep [19,37,41], some found more SDDCs in NREM than REM dreams [33], and others found similar SDDC rates for the two stages [40,46]. Therefore, no conclusions can be drawn regarding potential differences across sleep stages. Moreover, although some studies tried to stimulate both early and late in the night, specific time-of-the-night effects on SDDCs and their relationship to different sleep stages remain to be systematically evaluated.

4.3.5. *Stimulation-to-awakening interval*

The reviewed studies reported important methodological differences concerning the time interval between stimulation and dream report collection, which ranged from a few seconds to several hours. The impact of this variable is likely to be significant but has never been systematically addressed. Still, an increased SDDC probability has been shown for dreams collected during the second and fourth REM periods, even though only the second REM period had been stimulated [35].

Moreover, increased rates of incorporation were observed two (for NREM) to six (for REM) days after a TMR experimental session [21]. While preliminary, these findings suggest that SDDCs could occur with a delay spanning minutes, hours, or even days.

4.4. Sleep sensory disconnection and SDDCs

Dreams and SDDCs seem to have tight reciprocal links with the sensory disconnection mechanisms that preserve sleep continuity. Indeed, such mechanisms could filter out or attenuate some of the stimuli from the external environment. On the other hand, dreaming and SDDCs might be among the lines of defence adopted by the sleeping brain to tame potential sleep-disturbing stimuli.

4.4.1. The effects of sensory disconnection on SDDCs

Three main, non-mutually exclusive mechanisms have been suggested to sustain sensory disconnection during sleep [1,10]. The so-called 'thalamic gating' hypothesis [81] proposes that sensory information may be blocked or attenuated at the thalamus level before reaching the cortex. Related to this, the notion of 'cortical gating' refers to the fact that the information reaching sensory cortices may not propagate efficiently towards other cortical areas. Lastly, an 'informational gating' mechanism has been hypothesised to be active during REM sleep and dreaming experiences, when the focus of cognitive resources on endogenous processes could prevent sleepers from processing incoming sensory stimuli [82].

Sensory disconnection mechanisms likely have a key role in determining whether a stimulus will affect an ongoing dream. However, they may also determine a partial distortion of external stimuli, which may ultimately increase the variability and, therefore, decrease the detectability of SDDCs. Indeed, incoming information may be partially altered or attenuated before or at the cortical level. Moreover, while the dreamer is immersed in the oneiric experience, the stimulus may be misperceived or even entirely missed, just as someone busy on a particular task may fail to perceive or misperceive something happening out of their attention focus. Following this, expectancy based on the dream context and internal logic may bias the perception of the stimulus towards something that fits the ongoing oneiric setting. Inevitably, such effects could add up to the stimulus's alterations or attenuations that may have taken place at any previous processing step.

4.4.2. The role of SDDCs in sensory disconnection

A long-standing view, already proposed by Freud, is that dreams could represent the '*guardians of sleep*' [83; see also Supplementary Text S1]. In this view, when an external stimulus reaches the sleeping brain, "*either the mind does not concern itself at all with the causes of sensations' or 'if it is obliged to recognise the stimuli, […] the actual sensation is woven into the dream in order to deprive it of its reality*." In other words, when an external stimulus succeeds in reaching the dreamer's awareness, the brain might attempt to integrate it into the ongoing conscious stream, directly or through associations, to minimise potential effects on sleep continuity.

In line with this, two studies [[43,44]; also pilot data in [84]] suggested that arousal thresholds may be higher when stimuli are successfully incorporated into the dream experience than when they are not incorporated or when no dreams are experienced. Hence, dreams may provide a two-level protection: 1) at a lower level, the stimulus may fail to reach awareness because the dreamer's attention is focused on the internally generated experience ('*competition*'); 2) at a higher level, the stimulus may be integrated into the ongoing dream and is thus not recognised as an external and potentially arousing element ('*integration*').

Observations consistent with the sleep-protective role of SDDCs were also made in children aged 3 to 15 [85,86]. In a series of experiments with different stimuli and age groups, Foulkes observed that stimulus incorporation rates in REM sleep were close to zero for the youngest groups and tended to increase with age, whereas the probability for stimulations to induce body movements, indicating arousal, decreased substantially with age.

However, not all evidence supports the described relationship between incorporation and arousal threshold. Indeed, no differences were found between individuals with high and low arousal thresholds regarding incorporation [46]. Although this discrepancy could be explained using between-participant designs instead of within-participant designs, additional research is required to clarify the role of stimulus incorporation in sleep sensory disconnection.

4.5. Open questions and future directions

4.5.1. The neurophysiological correlates of SDDCs

Although none of the studies reviewed in the present work directly investigated the neural correlates of SDDCs, we discuss the possible relationship between SDDCs and typical stimulus-evoked responses such as (micro)arousals or K-complexes, and we propose some hypotheses regarding the functional mechanisms that may underlie the different SDDC types.

4.5.1.1. Microarousals. The presentation of sensory stimuli during sleep is often accompanied by activations of the arousal system and the appearance of microarousals. Some authors hypothesised that the occurrence of states characterised by wake-like activity may be necessary for SDDCs—and specifically for stimulus incorporation—to occur [46,53,54]. Following this viewpoint, several studies used 'cortical registration,' referring to microarousal-like responses in the EEG signal, as a trial-selection criterion indicating that the administered stimulus had reached the cortex [29,31–33]. However, only one study provided direct evidence in support of the arousal-dependency of SDCC, noting that stimulations followed by increases in alpha activity—typically accompanying microarousals—had a higher rate of incorporation relative to cases without alpha changes [53]. The apparent positive correlation between stimulus relevance and the probability of arousal response and incorporation [52,87–91], and the common observation that non-arousing odour stimuli almost never lead to stimulus incorporation [59–61] provide additional indirect supporting evidence. However, some authors reported no discernible differences in SDDC occurrence for stimuli followed or not by changes in alpha activity [29,34,67]. Moreover, evidence of SDDCs has been reported in experimental studies that excluded microarousals from the analyses [34,53]. These findings imply that, while visually detectable microarousals may be associated with SDDCs, they are unlikely to be a prerequisite for stimulus incorporation.

4.5.1.2. K-complexes. Sensory stimuli presented during NREM sleep are known to evoke K-complexes [84,92], but no studies have investigated the effects of these events on SDDCs. Since K-complexes reflect widely synchronised episodes of neuronal silence, they are commonly thought to have a sleep-protective function [93,94]. In fact, they have been suggested to quench incoming sensory information to promote sleep continuity [95,96]. According to this view, a stimulus that evokes a K-complex should not be capable of influencing the ongoing dream experience. Instead, K-complexes may briefly disrupt the stream of consciousness through a widespread suppression of brain activity. However, the subsequent increase in high-frequency activity or full-fledged arousals often observed after K-complexes suggests a temporary restoration of the brain's ability to integrate salient information [97,98]. This, in turn, could favour the processing and incorporation of stimuli administered after the K-complex. Altogether, it seems that both a suppressing and a promoting effect of K-complexes on SDDCs may coexist on different timescales.

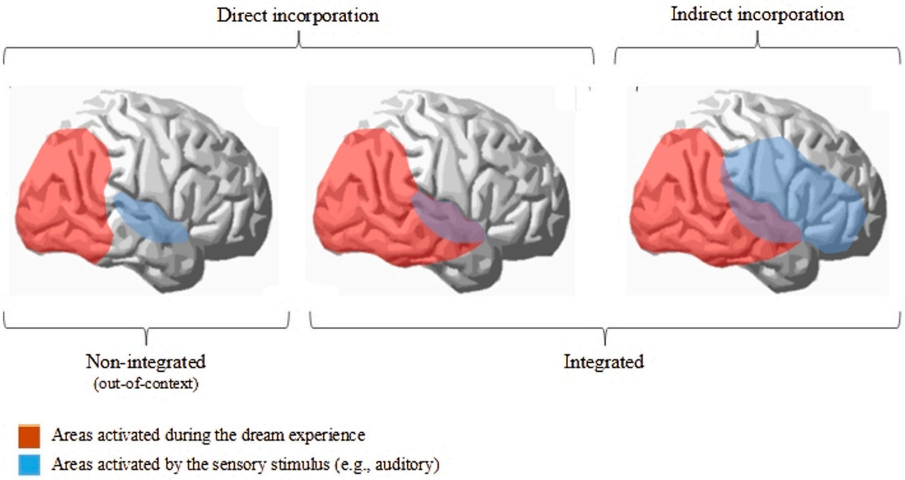

Fig. 5. Schematic representation of hypothetical neurophysiological mechanisms underlying the incorporation of sensory stimuli in dreams.

4.5.2. Functional mechanisms underlying SDDCs

The reviewed literature offered no hints as to which physiological mechanisms might underpin the distinct types of SDDCs. However, we may provide some hypotheses based on prior findings that showed a relationship between dream occurrence and local increases in wake-like activity, with the regional distribution of such activations corresponding to dream content [2,99,100]. Considering this, direct incorporations could be explained by stimulus-dependent activations of brain areas involved in low-level sensory processing. Moreover, whether the stimulus is fully incorporated into the dream or remains as an alien element may depend functionally on its coherence with the ongoing experience and physically on the relative integration of the newly engaged areas within the previously activated brain network [e.g., 101] (Fig. 5).

Cases of indirect incorporation might instead reflect the reactivation of brain areas storing memories somehow linked to the stimulus [102], implying a higher-level processing of incoming information. Interestingly, one could hypothesise that a similar process may be involved in some forms of dream modulation. Alternatively, dream modulation could emerge in response to non-specific activations of ascending, arousal-related systems targeting multiple brain areas. Future studies on SDDCs should combine a rigorous definition of SDDC types and advanced neuroimaging techniques, such as high-density EEG or simultaneous EEG-fMRI, to test these hypotheses.

4.5.3. Are we truly ‘disconnected’ during sleep?

A common assumption in sleep research is that differences in stimulus processing between sleep and wakefulness should inform us of how sensory disconnection occurs during sleep. However, our review revealed several important flaws in this logic. Evidence indicates that many stimuli not only reach the cortex and influence brain activity during sleep, but a significant portion of them may also be incorporated into the ongoing stream of consciousness. Still, understanding how and when this occurs is far from simple. Several factors, such as stimulus distortion or transformation, may prevent incorporations from being identified. In addition, dreamers may fail to report the perceived stimulus due to its potentially scarce relevance for the experience or an incomplete recall of the dream upon waking.

Real-time communication protocols with lucid dreamers overcome limitations related to dream retrieval and reporting [79,103], showing that dreamers might be able to consciously perceive -and even appropriately respond to-complex stimuli. Notably, one recent study provided evidence for transient windows of cognitive processing and behavioural responsivity to external stimuli during N1, N2, and REM sleep, suggesting that high-level stimulus processing may extend beyond the specific case of lucid dreaming [103]. While further research is required to clarify the frequency and nature of observed ‘sensory connection’ windows, we suggest that the conscious processing of external sensory information during sleep may be considerably more prevalent than previously believed.

5. Conclusions

The ability to manipulate oneiric experiences holds the promise of substantial scientific breakthroughs, ranging from understanding the origin and function of dreams to developing new treatments for clinical conditions associated with dream alterations. Consequently, the recent surge in dream engineering is unsurprising [e.g., 16,70,104]. The utilisation of sensory stimuli is particularly relevant among the various dream engineering techniques due to its reliance on well-established physiological pathways and functions, ease of implementation, and extensive history of anecdotal and empirical observations. However, the present review revealed a substantial lack of understanding of the processes regulating external sensory stimuli’s effects on dreams. We highlighted several major concerns and open questions, hoping this work will advance the field by stimulating novel, rigorous, collaborative research efforts.

Practise points

- Evidence shows that a non-negligible number of stimuli reach conscious awareness during sleep, contradicting the notion of sleep as a state of sensory disconnection. Considering this, the concept of dreams as a form of ‘disconnected consciousness,’ in which subjective experiences arise independently of the external environment, should be reconsidered.
- Direct incorporation may occur seamlessly by coherently integrating the stimulus within the ongoing dream narrative, or the stimulus may appear as an external, out-of-context element. In the second case, identifying the stimulus as an external element may trigger lucidity.
- Indirect incorporation happens when the stimulus is incorporated through semantic or mnemonic associations. Due to its potentially idiosyncratic nature, this form of incorporation may be difficult to recognise unless the dreamer is directly involved in the identification process.
- Dream modulations include all stimulus-dependent dream changes other than direct and indirect incorporation. They may manifest in many ways, making them difficult to predict and objectively identify.
- Somatosensory stimuli seem to show the highest SDDC induction rates among the evaluated sensory modalities. Overall, stimuli with high subjective or objective saliency seem more likely to induce SDDCs.
- Dreams may favour sleep continuity through two-level protection from external stimuli: 1) Competition with the ongoing conscious experience for attentional resources may prevent the stimulus from reaching awareness; 2) Integration of the stimulus into the oneiric narrative may spoil its arousing properties.

Research agenda

- Several fundamental questions remain to be addressed: 1) What determines the type of SDDC induced by a given stimulus?; 2) What are the neural correlates of

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SDDCs?; 3) Are certain pathological conditions (e.g., insomnia) associated with an altered likelihood or frequency of SDDCs?

- Future research should clearly specify the adopted definitions for SDDCs and dreams, as well as the specific queries used to probe conscious experiences upon awakening.
- A standardisation of the approaches used to identify SDDCs is necessary and could be achieved using computational linguistics methods, which may provide an objective and reproducible quantification of dream content.
- Certain features that could be identified as SDDCs may also appear spontaneously in dreams, highlighting the need for appropriate control conditions.
- Large-scale studies relying on multi-laboratory collaborations and open data sharing will be critical for addressing limitations associated with small sample sizes and investigating the role of inter-individual variability.
- Studies exploring the neural and functional bases of sleep sensory disconnection should assess subjective experiences to distinguish cases in which sensory stimuli are consciously perceived from those in which they fail to reach conscious awareness.

Declaration of Competing interest

The authors have no conflict of interest to disclose.

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Appendix A. Supplementary data

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