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CLINICAL REVIEW

Chronobiological features of dream production

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Summary A review of the scientific literature clarifies several chronobiological features of dreaming. The literature supports the conclusions that dreaming 'intensity' and, to a lesser extent dream-like quality, is modulated by (1) a sinusoidal, 90-min ultradian oscillation, (2) a 'switch-like' circadian oscillation, (3) a 12-h circasemidian rhythm, and (4) a 28-day circatrigintan rhythm (for women). Further, access to dream memory sources appears to be modulated by (5) a 7-day circaseptan rhythm. Further study of these rhythmic influences on dreaming may help to explain diverse and often contradictory findings in the dream research literature, to clarify relationships between dreaming and waking cognitive processes, to explain relationships between disturbed phase relationships and dream disturbances and to shed new light on the problems of dreaming's functions and biological markers. Further chronobiological studies of dreaming will likely enable the development of theoretical models that explain how interactions between and within major levels of oscillation determine the variable characteristics of dreaming.

Introduction

In the 50 years since discovery of a link between dreaming and the endogenous biorhythmic events defining REM sleep[1] there has occurred strikingly little convergence between chronobiology and the study of dreaming—despite a vast accumulation of research in both domains. While many of the findings in one of these domains has clear implications for understanding basic and applied questions in the other, there still is no comprehensive theory that links chronobiological concepts and findings to the processes of dreaming. The present work begins to redress this situation by reviewing evidence that is pertinent to the chronobiological nature of dreaming and briefly considering the types of chronobiological models of dream production that may be proposed. The orienting question of the work was as follows: *What is the nature of the empirical evidence linking dreaming processes to each of five different levels of chronobiological oscillation: (1) ultradian, (2) circasemidian, (3) circadian, (4) circaseptan and (5) circatrigintan?* Evidence was evaluated for four principal classes of dependent measures:

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dream recall presence/absence, dream length, dream content qualities and dream memory sources. It was expected that evidence would be found linking dreaming to biorhythms but that the different classes of dependent measures would be associated with different levels of oscillation. Further, it was expected that this approach would provide a more global view of the specific morphologies of rhythmic dream variables, morphologies that might lead to new hypotheses about dream mechanism and function. Finally, it was expected that findings from the review would help lay some groundwork for development of new chronobiological models of dreaming. Considerations for the development of such models are discussed in more depth at the end of the paper.

Note that here the term dreaming is used in an inclusive sense equivalent to that of sleep mentation, i.e. the occurrence of any subjectively experienced cognitive events during sleep.

Ultradian rhythms

Transitions between REM and NREM sleep are widely viewed as 'switch-like' in nature, flipping rather abruptly from one type of sleep to the other. Some measures, such as Delta EEG power, display marked switch-like transitions at the onset and offset of REM sleep. However, studies of multiple physiological systems indicate that REM–NREM transitions are, in fact, much more sinusoidal than typically acknowledged.[2] For example, the polarity of neurons driving REM sleep onset demonstrates a more graduated, oscillatory fluctuation that begins well before the onset of EEG-defined REM sleep.[3,4] Research that has sampled dreaming at multiple points within and between REM and NREM sleep suggests that dreaming more closely conforms to a sinusoidal, oscillatory phenomenon than a switch-like one. This is the case for dependent measures implicating both (a) frequency or length of recalled dreams and (b) quality of reports. These measures are discussed in separate sections below.

Frequency/length of recalled dreams

Within-stage changes

The length of a dream report is typically assessed by either (1) a count of its non-redundant content-bearing words, Total Recall Count (TRC)[a] or

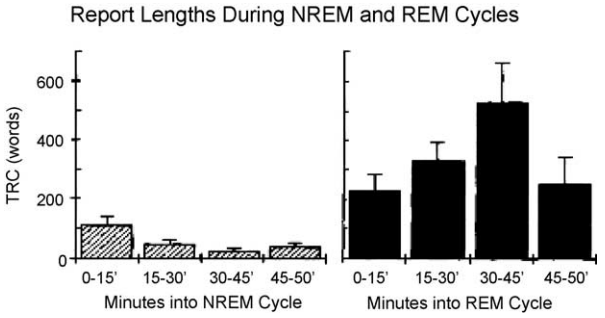

Figure 1 Report lengths for dream reports from NREM and REM periods of different durations. (A) Mean (SEM) report length as a function of elapsed time in stage for 88 REM and 61 NREM reports (from Hobson et al.[2]); (B) Median (SEM) report length as a function of elapsed time in stage for 264 REM and 247 NREM home reports ($N=16$ subjects; from Stickgold et al.[10]).

log(TRC+1) (e.g. Ref. 5), or (2) the number of temporal units[b] (TU)[6,7] comprising the report.[8] Report length is widely thought to measure cortical activation and, thus, the overall 'quantity' of output of a dream mentation generator.

By either measure, REM sleep reports are consistently longer than NREM reports. These measures also suggest that dream output over consecutive REM and NREM episodes oscillates in an ultradian pattern. When relationships between report length and time elapsed in REM or NREM sleep are assessed, report length fluctuates sinusoidally over time[9] (see Fig. 1). For dreams from REM sleep (black bars), length estimates are lowest 0–15 and 45–60 min after REM onset, and highest for times in between. For dreams from NREM sleep (white bars), an *opposite* pattern is observed. A similar sinusoidal pattern was found in a second study.[10] These results complement earlier work that sampled dreaming at either 5 or 15 min into the REM period and found longer reports in the latter condition.[11]

The results in Fig. 1 are highly suggestive of a sinusoidal function and thus of an ultradian oscillation in report length that is active both within and between sleep stages. The findings are also consistent with several additional studies that assessed dream length as a function of increasing distance from prior REM sleep. In four studies,[12–15] NREM dream reports were either more probable or of longer length when sampled in close proximity (at 5 min) rather than more distally (10, 30, 12 and

[a] TRC is typically defined as the number of non-redundant, content-bearing words in a report excluding hesitations, speech errors, repeated words and commentary; TRC is log-transformed to minimize the effect of extremely long reports.

[b] Temporal unit (TU) identification is based upon reported activities; synchronously occurring activities define a single TU. Whenever a character performs a new activity, responds to another character or changes topics in a conversation a new TU is scored.

15 min, respectively) from prior REM sleep. Also consistent with the preceding, a fifth study[16] demonstrated that duration of NREM sleep preceding an awakening was negatively correlated with report length.

The likelihood that report length reflects an ultradian oscillatory process, which all of the preceding evidence supports, may explain the seemingly non-confirmatory finding[17] that report length differences for REM periods of 5- and 10-min duration were small ($M=413$ vs. 325 words, $p=0.114$). This may be attributed to random variation in the measurement of dream reports sampled very close together on an ultradian curve, which minimized the likelihood of detecting gradual changes.

Between-stage changes

REM and NREM dream reports presumably reflect activity of an imagery generator functioning at the opposite extremes of its ultradian period. Large differences in dream recall and length would thus be anticipated and, in fact, are reliably observed. That dream reports are more probable and longer after REM than after NREM awakenings are among the most highly replicated findings in the dream research literature (see reviews in Refs. 2 and 4). Fig. 2 shows the marked differences in levels of dream recall from REM and NREM sleep in summarizing 38 studies conducted between 1953 and 2004. The two most recent studies in this figure[18,19] are noteworthy because extremely low probabilities of recall were found for NREM sleep. Both studies employed methods which greatly minimized the possible confounding influence of prior REM sleep on NREM dream recall.

Paralleling the differences in Fig. 2 are similarly large REM–NREM differences in dream report length; REM:NREM ratios in TRC vary from 2:1 to as high as 5:1.[10] Much of the variability observed for both measures of recall and length may be due to the fact that experimental protocols have not consistently controlled for phase relationships between REM and NREM sampling points. The use of a constant time-in-stage preawakening delay for both REM and NREM sleep (e.g. 10 min for both) guarantees neither similar phase relationships to the ultradian peak (for REM) and nadir (for NREM) nor constant phase relationships between the REM and NREM samples for several reasons: (a) REM and NREM sleep occupy different proportions of the sleep cycle (e.g. 20% REM; 80% NREM), (b) the proportions of REM and NREM sleep change across the night, and (c) the periodicity of the 90-min REM-NREM cycle is highly variable.[20] On the other hand, the common procedure of sampling mentation with *progressive temporal delay into stage* (PTDIS) protocols, e.g. 5 min into the first REM, 10 min into the second REM, 15 min into the third REM, etc. further confounds ultradian phase with time-of-night (see also below).

Quality of dream reports

Within-stage qualitative changes

As is the case for measures of dream recall and length, much evidence indicates that the vividness, intensity, dreamlikeness and other qualities of

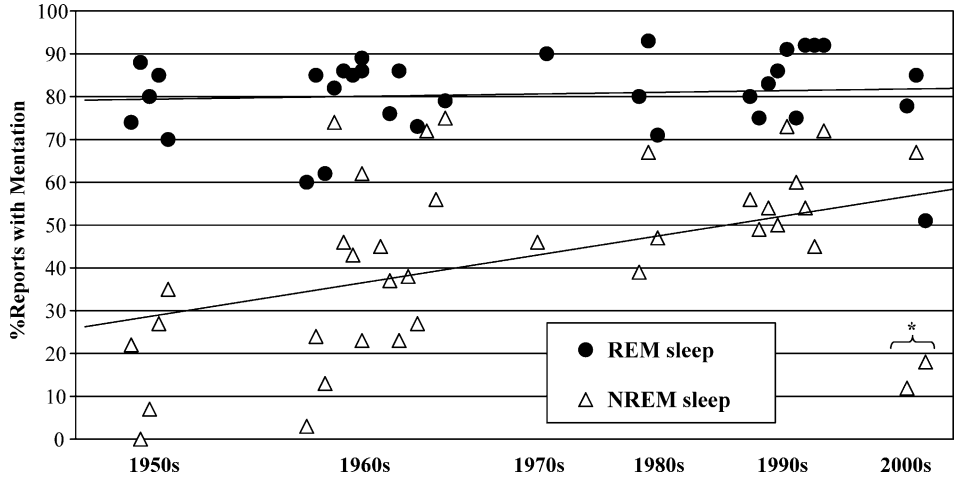

Figure 2 Percent recall of dreaming from REM and NREM sleep awakenings in 38 studies from 1953 to 2004. Variation in recall from NREM sleep is attributable in part to changing definitions of dreaming, in part by non-standardized choice of awakening times for dream sampling and in part from uncontrolled sleep stage interactions. Flagged values for very low NREM recall in 2001 and 2004 studies reflects use of the Sleep Interruption Technique[19] and an ultra-short sleep/wake schedule,[18] both of which minimize possible confounding influences on dreaming of prior REM sleep on NREM dream recall.

dream imagery increase progressively within REM sleep periods; some evidence suggests that these qualities may decrease within NREM episodes. Unlike the findings for recall and length, however, clear sinusoidal variation of these measures has not yet been established.

For REM sleep, subject ratings indicate that dream reports from 'long' REM sleep episodes (9 min or more) become more dreamlike in several respects than those from 'short' episodes (1 min or less).[21] Long REM sleep reports are more active, distorted, dramatic, emotional, anxious, unpleasant and clear or vivid and contain more different scenes, more scenes with clear visualization and more socially unacceptable content (violence/hostility) than short REM sleep reports. Consistent results were obtained when dreams were sampled from REM periods of several different lengths.[22,23] In the latter study, 4 male college students were each awakened twice from both REM2 and REM4 for each of six conditions: 0.5, 2.5, 5.0, 10, 20 and 30 min after REM onset, and asked to rate 12 qualities of their dreams. *Recall, emotion, anxiety, pleasantness* and *clarity* showed linear increases over time. Three variables (*emotion, anxiety, pleasantness*) had additional trend components leveling off at 10 min, in some cases declining at 20 min, and increasing again at 30 min.[22] These trends suggest a time course with two major peaks at 10 and 30 min[23] which parallels distributions of REM density across a REM episode.[24] It is also possible that the biphasic trend in these results is due to interactions between ultradian factors (causing the plateau at 10–20 min) and circadian factors (causing an additional increase at 30 min). Others[25,26] report that plausibility and sensibleness of dreams in relation to daily life do not change as a function of REM length.

For NREM sleep, evidence again points to relationships that are *opposite* in direction to those observed for REM sleep and thus supports the notion that the measures reflect activity on the descending slope of an ultradian oscillation. In one study,[27] Dreamlike fantasy (Df)[c] scale scores[28,29] were lower ($p < 0.10$) for reports from 20-min NREM (Stage 4) episodes than for 5-min NREM episodes, even though the reports were matched within subjects and for time of night. In a second study,[14] NREM (Stage 2) reports obtained 12 min after the end of REM sleep episodes were rated as less dream-like (M rating $= 4.17$) than were NREM reports obtained 5 min after REM sleep episodes ($M = 4.73$, $p < 0.001$).

[c] The DF Scale is an eight-item scale: 0, no recall (mind was blank); 1, no recall (mind not blank, but forgets); 2, content is conceptual (no sensory imagery), everydayish; 3, content is conceptual, bizarre; 4, content is perceptual (sensory imagery), non-hallucinatory (did not believe it was real), everydayish; 5, content is perceptual, non-hallucinatory, bizarre; 6, content is perceptual, hallucinatory (believed it was real), everydayish; 7, content is perceptual, hallucinatory, bizarre.

Between-stage qualitative changes

A large body of research (see reviews in Refs. 2 and 4) demonstrates that REM sleep reports are consistently more perceptual, hallucinatory, emotional, dramatic, physically involving, rich with characters and visual scenes than are NREM reports, while the latter are more conceptual, thoughtlike and mundane.[21] However, these highly replicable findings are not easily interpreted as due to ultradian processes because of their possible confounding by the consistent differences in report length described earlier. Because REM reports are consistently longer than NREM reports, it has been argued that the two may be compared only if this difference is removed or statistically controlled, e.g. by comparing reports of equal length, calculating proportions with a common metric (e.g. TU), or removing report length as a covariate. The use of such procedures has caused significant qualitative differences between REM and NREM dream reports to disappear in some studies.

Most length control procedures have been criticized on methodological grounds (see reviews in Refs. 2 and 4) and there is evidence that the qualitative nature of sleep mentation changes as a function of the REM–NREM cycle even with report length controlled (see review in Ref. 4). In brief, even with length controls, REM dream reports surpass NREM dream reports on measures of self-reflectiveness,[30] bizarreness,[31] visual and verbal imagery,[5,31,32] movement imagery,[33] characters and self-involvement,[6] self-representation[6] psycholinguistic structure[34] and narrative linkage.[35]

Memory sources

Memory sources that subjects are requested to furnish in association to their dreams are another form of evidence that REM and NREM dream reports differ, although it remains unknown whether these differences are attributable to an ultradian oscillator. Results from several studies indicate that NREM dream sources are primarily biographical episodes (episodic memories) while REM sources are a mixture of episodic and semantic memories.[36,37] The predominance of episodic sources for NREM dreams maintains regardless of time of night and independent of correction for report length.[7,37–39] It is thus possible that an ultradian memory process

oscillating between access to primarily episodic vs. primarily semantic types of memories partially determines the content of REM and NREM dreaming. Within-stage oscillations in memory sources consistent with such a possibility have not yet been demonstrated, however.

In sum, most results from quantitative and qualitative assessments can be explained as due to an oscillatory ultradian modulation of dreaming processes. REM and NREM dream reports thus reflect the output of a dreaming generator that is sampled at varying points along its rising and descending slopes. There is yet no indication of whether different components of dreaming, such as access to memories, choice of imagery content, or intensity of emotion, are modulated by different ultradian processes or about how the desynchronization of such processes might affect the presence or form of dreaming. Further study is clearly needed which controls both time in stage and time of night sources of variation without confounding the two.

Basic rest-activity cycle (BRAC) hypothesis

Kleitman's proposed ultradian BRAC hypothesis[40] has been a stimulating heuristic that conceptually links the 90-min REM–NREM rhythm with circadian oscillations. One study of BRAC and dreaming suggested a continuation of the REM–NREM cycle and dreaming during the daytime in the form of fantasy fluctuations. Results for a series of individual subjects and a separate group of normal subjects indicated that the intensity of daytime fantasy fluctuated with a 90-min periodicity.[41] When these results were pooled with results from 3 additional experiments and assessed with superior statistical procedures, the effect was not clearly replicated; only a 200-min ultradian rhythm was demonstrated.[42] On the other hand, there is ample support for the existence of daytime ultradian fluctuations in cognitive performance.[42–44] Correlations between daytime imagery abilities and dream recall frequency have also been reported.[45] Such procedures could be adapted to assess whether rhythmicities in dreaming possess waking-state counterparts in a manner predicted by the BRAC hypothesis. Additional findings pertinent to this hypothesis are reviewed in a later section on circadian rhythms.

Circasemidian rhythms

Broughton[20] has argued convincingly for the existence of 12-h or circasemidian rhythms that are either distinct from 24-h circadian rhythmicities or a subcomponent of their expression. Accumulating evidence supports the 12-h rhythm in sleep propensity (post-lunch sleepiness), SWS expression,[46] EEG power[47] and other processes (see Ref. 20, for review). Although this rhythm explains the global human tendency to nap in the early afternoon, research examining circasemidian characteristics of dreaming are few. A single study[18] using an ultra-short (20/40m) sleep/wake schedule with dream sampling at each awakening over three consecutive days ($N=11$ males, M age $=22.4\pm2.1$ yr) provides some support for a circasemidian oscillation in dream intensity (see Section 4.3.1). While the scale employed (0, none; 1, a little; 2, a moderate amount; 3, a lot) to the question *How much did you dream?* may have produced a ceiling effect for REM sleep reports, for NREM reports both an acrophase at 08:00 and a secondary peak at 16:00 are visible in the time-plotted results.

It should be noted that because most purportedly circadian measures of dreaming are usually undersampled (i.e. measured only during the night portion of the 24-h cycle), many results described in the circadian rhythms Section could be explained alternatively as due to the influence of circasemidian factors.

Circadian rhythms

Circadian features of dream content are difficult to validate because, strictly speaking, their measurement is limited to the nocturnal portion of the sleep/wake cycle. A waking analogue of dreaming, such as spontaneous fantasy (see above), or a reliable 24-h physiological correlate of dream-related processes, of which none yet exists, would be needed to convincingly demonstrate a circadian oscillation for dreaming. In lieu of such measures, trends across the night can be assessed for whether they are at least consistent with the hypothesis of a circadian influence. Such trends in dreaming can be further evaluated for their relationship to known fluctuations in waking state processes that have face validity as possible waking state analogues of dreaming, e.g. spontaneous fantasy or hemispherically lateralized processes.

Findings from several research groups are generally consistent with the notion that across-the-night changes in dream length, content, organization and memory sources are modulated by circadian clocks. Some of the findings demonstrate progressive changes across the night that are

Table 1 Studies showing quantitative and/or qualitative changes in sleep mentation across the night.

Study, sleep stage	No. of S's	Methods and awakenings	Quantitative findings	Qualitative findings
Domhoff and Kamiya,[53] REM	22 College students (14m, 8f)	Total $N=219$ reports (73/R)		R1 > R2, R3 (characters, aggression/misfortune, buildings as settings) R1 > R2, R3 (terrain/ country as settings) R1, R2 > R3 (room settings) R1, R2 < R3 (sexual acts, food elements)
Foulkes;[21] Foulkes and R1 < R2, R3 (perceptual content)	Rechtschaffen,[54] REM	22 Students or University employees, 'mostly in 20's' drawn from larger sample (13m, 11f)	PDTIS Schedule (5R1, 10R2, 20R3)	
Pivik and Foulkes,[52] NREM	20m young adult college students	Two consecutive nights Four WU/night: SO30, 30NR1–30NR3	NR1 < NR2, NR3, NR4 (Recall%)	NR1 < NR2, NR3, NR4 (Df score)
Van de Castle,[58] REM	15m college students	*Multiple series*. 273 reports/R *Single series*. 196 reports for R1–R4		*Multiple series*. R1–R3 < R4–R8 (clarity, misfortunes, bizarre, female characters, color elements) *Single series*. R1 = R2 = R3 = R4 (all measures)
Tracy and Tracy,[27] NREM	11m, 10f young adults $M_{AGE}=21$ yr	Three non-consecutive nights Five-min samples of (a) descending stage 2 and (b) stage 4 sleep—also 20 samples of stage 4		$NR_{EARLY} < NR_{LATE}$ (Df scale)
Cohen,[57] REM	10–23m college students	Left (LH) and right (RH) hemisphere processes: (dream recall quality, presence of verbal activity, high ego functioning, positive emotion, active participation)		Five replication studies. (*LH*. Increase across night in all studies; *RH*. Few or inconsistent changes in all studies)
Arkin,[14] NREM	40m college students (18–26 yr)	One night each NR(S_2) reports during R deprivation and NR-control deprivation, first and second halves of night		$NR_{EARLY} < NR_{LATE}$ (DLQ)

(*continued on next page*)

Table 1 (*continued*)

Study, sleep stage	No. of S's	Methods and awakenings	Quantitative findings	Qualitative findings
Kramer et al.,[55] REM	25 (14m, 11f; 20–25 yr)	20 Consecutive nights WU at 'end' of R1–R4		Hall and Van de Castle (1966) frequency variables[29]. R1–R2: increase in 15/41 variables; R2–R3: increase in 6/41 variables; R3–R4: increase in 7/41 variables
Waterman[5,49], REM	24m, 12 elderly (M_{AGE} = 65.1), 12 young (M_{AGE} + 22.9)	Four consecutive nights 4. 8–5.0 min into all R nights 3 and 4 = three WU/night: early (0.0–2.5 h), middle (2.5–5.0 h), late (5.0 h)	*Young S's*. $R_{EARLY} < R_{MIDDLE}$, R_{LATE} (TRC); $NR_{EARLY} < NR_{MIDDLE} < NR_{LATE}$ (TRC) *Elderly S's*. R_{EARLY}, $R_{MIDDLE} < R_{LATE}$ (TRC); NR_{EARLY}, $NR_{MIDDLE} > NR_{LATE}$ (TRC)	*Young S's*. $R_{EARLY} < R_{MIDDLE}$, R_{LATE} (visual imagery); $NR_{EARLY} < NR_{MIDDLE} < NR_{LATE}$ (visual imagery) *Elderly S's*:. R_{EARLY}, $R_{MIDDLE} < R_{LATE}$ (visual imagery); NR_{EARLY}, $NR_{MIDDLE} > NR_{LATE}$ (visual imagery)
Rosenlicht et al.,[17] REM	22 (12m, 10f; 19–27 yr)	Two consecutive nights Three WU/night in SO, R2, R4 Five or 10 min into R counterbalanced across nights	R2 < R4 (TRC)	
Casagrande et al.,[31] REM, NREM	20 Right-handed college students (4f, 16m; 20–27 yr)	Five consecutive nights; 4 and 5 for dream recall: 5R2 (R_{EARLY}), 5R3 (R_{LATE}), $5S_2$2 (NR_{EARLY}); $5S_2$4 (NR_{LATE})	$R_{EARLY} < R_{LATE}$ (%recall); $NR_{EARLY} < NR_{LATE}$ (logTRC)	$R_{EARLY} = R_{LATE}$ (visual imagery); $NR_{EARLY} < NR_{LATE}$ (visual imagary)
Cipolli et al.,[50] REM	16m college students (19–24 yr)	Five nights; nights 2, 3 and 4 = 4 WU/night (9 min into R1–R4)	R1 < R2, R4 (no. of statements in event structure); R1 < R2 < R3, R4 (no. of episodes/story); R1 = R2 = R3 = R4 (no. of setting statements)	
Agargun and Cartwright,[56] REM	26 (10m, 16f) with major depression (13 suicidal, 13 non-suicidal)	Three consecutive nights; night 2: baseline; night 3: PDTIS schedule (5R1, 10R2, 15R3, 20R4)		Increase in DLQ from early to late half of the night. *Suicidal*. $R_{EARLY} < R_{LATE}$ (freq. negative affect); $R_{EARLY} > R_{LATE}$ (freq. positive affect) more DLQd, i.e. Df decrease R_{EARLY} to R_{LATE}. *Non-suicidal*. More DLQd +

DLQ: dreamlike quality; DLQd: DLQ difference; LH: left hemisphere; RH: right hemisphere; NR: NREM sleep; R: REM sleep; SO: sleep onset; TRC: total recall count; WU: wake up; PTDIS: progressive temporal delay to stage; PTDIS protocols are detailed according to the following examples: 5R1=5 min into first REM episode; $5S_2$4=5 min into forth Stage 2 episode, etc.

consistent with a sinusoidal 24-h rhythm, while many others suggest that changes are exponential or 'switch-like,'[48] with marked differences occurring between reports from the first third of the night and all later sample points (see Table 1). Both types of finding may be explained by circadian factors; however, they may also be explained by linear, non-oscillatory factors such as sleep homeostasis. The convergent results from a few key studies are thus critical in that they tend to favor the circadian modulation explanation of dreaming. These results are described in a later Section.

Recall and report length changes across the night

Measures of dream report length described earlier have also been applied to studies of mentation across the night and provide information about potential circadian characteristics.

REM sleep effects

A study that experimentally varied both ultradian and circadian factors[17] found that dream reports from early REM periods (REM2) were shorter than those from later periods (REM4). The TRC measure was twice as long for REM4 than for REM2 and this difference was highly significant for awakenings 10 min into REM sleep ($p=0.001$) and marginal for those 5 min into REM sleep ($p=0.07$). Similarly, in a study comparing young adults' dream reports from early (0.0–2.5 h), middle (2.5–5.0 h) and late (5.0–7.5 h) night awakenings, all 4.8–5.0 min into REM sleep, an exponential lengthening (in TRC) was seen from early to middle awakenings and a plateau from middle to late.[5,49] For older subjects, the increase in length occurred only in the middle-to-late comparison.

The previous effect for young adults was replicated[50] with mentation sampled from the first four REM periods in a study controlling for ultradian factors (awakenings all were 9 min into each REM period). Time-of-night effects for several 'story structure' measures included: number of statements in the event structure ($p<0.001$) and the number of episodes/story ($p<0.001$). For the former measure, REM1 dream reports possessed significantly fewer statements than REM2 to REM4 reports while for the latter measure, the order of means was REM1 < REM2 < REM3, REM4. No time-of-night effect was found for the number of statements describing settings.

These findings are consistent with results from our study of 20 male (age: 26.5±7.5 yr) and 20 female (27.4±8.9 yr) healthy subjects awakened from various REM sleep periods.[51] Measures of both probability of recall and mean TRC ($N=135$ reports total) were lower for REM1 than for REM2 to REM5 (see Fig. 3, panel a). In this study, REM awakenings were implemented with a PDTIS protocol (5 min first REM; 10 min second REM; 15 min third REM; 20 min fourth–fifth REM) and may therefore be confounded by ultradian factors.

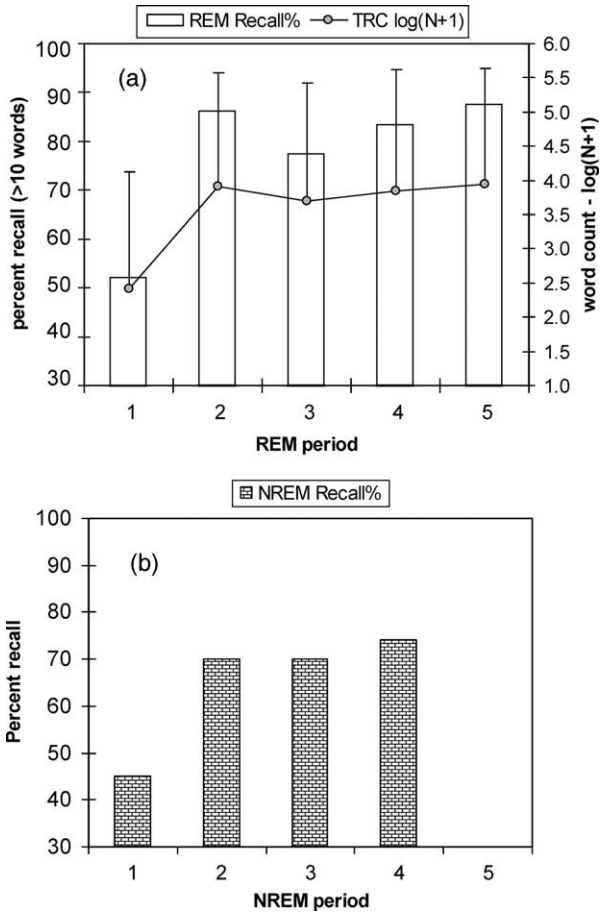

Figure 3 Percent recall and mean total recall count (TRC) for dream reports collected across the night from REM sleep (a)[51], and NREM sleep (b)[52]. Exponential ('switch-like') increases from first to second sleep cycles appear in both graphs. Values for NREM period 5 are not available.

NREM sleep effects

Findings for NREM sleep mentation parallel those for REM sleep. Pivik and Foulkes[52] conducted four awakenings per night, the first 30 min after sleep onset, the second, third and fourth 30 min into NREM periods that followed the first, second and third REM periods, respectively. For NREM stages 2, 3 and 4 combined, the percent of awakenings bearing some mental content was low for NREM1

(45%), rose dramatically for NREM2 (70%) and remained relatively high for NREM3 (70%) and NREM4 (74%; see Fig. 3, panel b). This effect was due primarily to changes in stage 2 rather than stages 3 or 4 sleep, e.g. stage 2 recall from the first and second NREM periods increased from 29 to 83%; for stage 3 reports recall was relatively constant for these two times—60 and 61%, respectively.

Similarly, in the Waterman[5,49] study described earlier, dream reports were evaluated for NREM (Stage 2) awakenings in early, middle and late parts of the night. For young subjects, NREM report length increased linearly across the three sample times. For older subjects, however, report length remained high and steady from early to middle samples then dropped sharply from middle to late.

Quality of report changes across the night

A great deal of research indicates that dreaming becomes more subjectively realistic and engaging in later sleep cycles and again suggests that dreams sampled in the first or second sleep cycles differ markedly from those in subsequent cycles. These qualitative changes are typically confounded by changes in report length and the same caveats about length described earlier for ultradian rhythms also apply here.

Qualitative REM sleep effects

An early study[53] of dreams (N = 219) collected from each of the first three REM periods and rated on 20 scales found REM2 and REM3 reports to differ from REM1 reports for several scales: more characters, more aggression/misfortune elements, more buildings and fewer terrain settings. However, for some scales a change occurred only from REM2 to REM3: more sexual acts, more food elements and fewer room settings.

Several groups have conceptually replicated such across-the-night patterns of change. First, there are positive correlations between time of night of the REM period awakening and ratings of mentation vividness ($p = 0.01$) and emotionality ($p = 0.05$).[26] Second,[21,54] subject ratings ($N = 22$) on several variables revealed that REM1 dream reports differed more from REM2 reports than the latter did from REM3 reports. Third,[55] dream reports from young adults ($N = 25$) rated by judges showed marked changes (increase in 15/41 variables) from REM1 to REM2 and less marked changes from REM2 to REM3 (6/41 variables) and REM3 to REM4 (7/41 variables). Fourth, the dream reports of healthy volunteers ($N = 13$) increased in Dream Like Quality (DLQ)[d] from early (REM1 + REM2) to late (REM3 +) sleep,[56] including an increase in *strongly emotional* content (from 16.7 to 23.1%) and *positive emotion* (from 15.4 to 38.5%) and a decrease in *neutral emotion* (69.2–46.1%).

Confounding of the preceding results by ultradian factors unfortunately limits their generality. Two studies[21,56] confounded REM period order with prior stage duration due to a PDTIS protocol (5 min first REM; 10 min second REM; 20 min third and later REMs). Another[55] likely confounded REM period order with length because all awakenings targeted the 'end' of the REM episode (first REM periods are typically shorter than later periods). In another study,[26] a partial PDTIS protocol was used, REM1 awakenings were always short (i.e. 5 min) whereas all other REM awakenings were counterbalanced between short and long (i.e. 5 vs. 12 min).

Despite potential confounding of these studies, their results are nevertheless consistent with findings from studies which control for such confounds. Waterman[5] controlled the ultradian confound by performing awakenings 4.8–5.0 min into each REM period. A visual imagery measure—a count of visual nouns, action words, modifiers and spatial relations—clearly increased across the night, with marked changes for the early-to-middle night comparison but not for the middle-to-late night comparison. Confound effects are also mitigated by evidence[32] that circadian and ultradian factors do not interact statistically in subjective ratings of dream vividness and other features (see below).

Another early series of five replication studies[57] that minimized confounding ultradian effects (awakenings 5–10 min post-REM sleep onset) reported results consistent with the preceding support for a circadian interpretation. A within-night pattern of increases in left hemisphere (LH), but not in right hemisphere (RH), processes was observed. In all studies, a combined LH score increased significantly across the night. This pattern is consistent with the influence of a LH circadian process with an early morning acrophase whereas a consistent lack of variation in RH processes suggests either no circadian variation or a possible rise and acrophase later in the day. The latter case would imply that LH and RH influences on dreaming are modulated by separate circadian oscillators (see discussion below).

[d] DLQ, a five-point scale: 1, no recall; 2, a non-perceptual report; 3, a single visual image; 4, two or more images with some story connecting them; and 5, two or more images with an elaboration of detail and a well-developed narrative.

Mixed support for a circadian effect is found in a study (see Ref. 58, for summary) of male college students ($N=15$). A 'multiple' series of dream reports collected after every REM period for several nights (N reports $=273$) indicated change over REM periods using both objective and subjective types of measures, i.e. more single female characters, more misfortunes, more clarity, easier to recall, more bizarre and more color elements in later REM dreams. In contrast, a 'single' series of reports collected from subjects who were awakened only once per night for the first four REM periods ($N=196$) gave no comparable evidence of change. These findings might question whether the within-night changes seen in laboratory studies are artifacts induced by multiple awakening schedules; however, the methods of the study remain unpublished and cannot be evaluated for rigor and potential confounding variables.

Two studies that seemingly fail to suggest a circadian effect on REM sleep measures of visual and auditory imagery and bizarreness[31,32] are nonetheless explainable as due to circadian factors. In both experiments, although imagery vividness and bizarreness ratings did not differ between 'early' and 'late' REM period awakenings, 'early' REM reports were drawn only from REM2 and 'late' reports from REM3. Consistent with the 'switch-like' variations found in other studies, the expected increases in dream intensity may already have taken place prior to REM2 in these studies.

Another possible confound in laboratory research is raised by the Antrobus[32] study. Since, as they demonstrated, dream vividness is more pronounced after delaying sleep onset by 3 h—presumably by forcing dreaming to occur further along the rising edge of a circadian activation process—the habitual vividness of REM dreams and the relative differences among REM dreams of the same night may be dramatically altered if lights out is delayed. Vividness may be influenced in proportion to the time that a subject's normal bedtime is inadvertently delayed by, e.g. electrode installation, equipment calibration, questionnaire administration, and other routine presleep tasks.

Qualitative NREM sleep effects

Within-night patterns similar to those reported for REM sleep have been observed for NREM reports in several studies that control ultradian confounds. First, Df ratings of NREM reports collected across the night were low in NREM1 compared with NREM2 to NREM4[52]. Second, there was an increase in NREM (Stage 2) dreamlike quality from the first to the second half of the night in the reports of male college students.[14] Third, NREM (Stage 2) visual imagery scores increased linearly across early, middle and late thirds of the night in young subjects.[5] Fourth, visual imagery ratings of NREM (Stage 2) reports were higher in NREM4 than in NREM2—even after covarying report length.[31]

Memory sources

Memory source studies provide additional information about possible circadian influences on dream formation, specifically, evidence consistent with the claim that circadian influences affect some, but not all, types or features of memory sources and that these effects may interact with ultradian factors. The principal methods use either objective markers of memory sources, such as laboratory incorporations, or subjective markers, such as subject associations to recalled contents. The memory features most often evaluated are (1) the informational quality of the sources (semantic vs. episodic) and (2) the temporal recency of the sources (recent vs. remote events).

Information quality of memory sources. A within-night effect was reported for semantic memory elements identified for REM, but not NREM, dreams.[38] Dreams were reported ($N=16$ subjects) after 5 min into REM1 and REM3 and after an unspecified time into NREM1 and NREM3. Dream sources were elicited and rated by judges as either strict episodes,[e] semantic knowledge or abstract self-references.[38] For REM reports, only semantic sources were less frequent for early (16.4%) than for late (31.9%) awakenings ($p=0.027$), even when report length was controlled.

However, when the raw data from the preceding study were combined with those from other (larger N) studies, the within-night effect on semantic sources for REM dreams disappeared[37] while the absence of other effects (episodic, self-reference) was confirmed. Unlike the previous study, a new, significant within-night effect for NREM sleep reports was observed ($p=0.014$) but its morphology was unfortunately not specified. Finally, a stage difference in episodic sources (NREM > REM) was found to be constant throughout the night, suggesting an ultradian, but not a circadian effect.

[e] (a) *Strict episode*. Discrete episode in the life of the dreamer, with precise spatial and/or temporal coordinates; (b) *Abstract self-reference*. Memories not connected to any particular spatiotemporal context, referring to the dreamer's general knowledge of him/her self and his/her own habits; (c) *Semantic knowledge*. Elements of general knowledge of the world, including episodes from the biographies of others.

While these studies provide conflicting evidence for modulation of access to semantic memory sources across the night, they concur in supporting an *absence* of such modulation for either episodic or self-reference source types.

Temporal recency of memory sources. Studies evaluating the timing of memory sources provide findings discordant with those assessing their informational quality. Several early studies indicate that memory sources referring to temporally recent (presumably episodic) events are preferentially associated with early (vs. late) night dream reports. For example, a case study[59] reported that early night dreams referred often to the laboratory experiment whereas later dreams referred to early childhood or adolescent memories.

Two studies confirmed this finding. In one,[60] subjects associated recent memory elements to their early night REM dreams and remote elements to their late REM dreams. In another,[26] recent elements were associated to dreams from the first 3.5 h of sleep, remote elements to dreams from 3.5 to 7.5 h, and moderately recent elements to dreams from later than 7.5 h. Temporal remoteness of associations was also correlated with body temperature.

A subsequent study[61] confirmed these findings among subjects who wore red-tinted goggles over 5 days and reported dreams after multiple REM period awakenings. On the first post-exposure night, colors from the red end of the spectrum ('goggle' incorporations) occurred only in REM1 dreams. On subsequent nights (2 and 3) incorporations spread to REM2 and REM3 dreams and on nights 4 and 5 to REM4 and REM5 dreams. Thus, incorporations of new (same day) experiences were restricted to *early* REM periods; progressively older experiences were processed in *later* REM periods.

Experimental and pathological desynchronization of circadian factors

Some of the most compelling evidence for the existence of circadian influences on dreaming is found in studies in which relationships between circadian factors and dreaming are desynchronized either by experimental design, by pathological factors such as depression, post-traumatic stress disorder (PTSD) and jet lag, or by aging. In all cases, there occurs a situation in which dreaming is atypically intensified early in the sleep episode while circadian rhythms appear to be phase-advanced relative to the habitual sleep period.

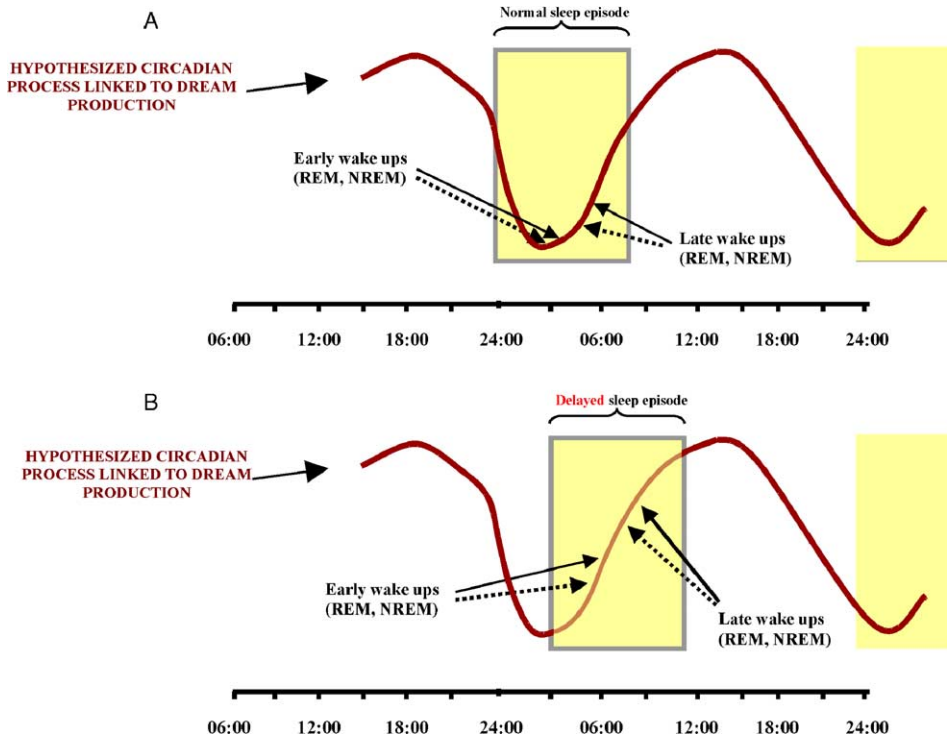

Figure 4 Theoretical model underlying partial forced asynchrony protocol used to manipulate hypothesized circadian influences on dream formation. Awakenings for report collection in the normal sleep, no delay condition (A) were made Early and Late in the sleep episode. Awakenings in the Delayed sleep condition (B) were made at the same times relative to sleep onset, thus, at different phase relationships to the hypothesized circadian process (i.e. on its rising phase). As predicted, dream vivification was increased for the late night reports in the Delayed condition (Adapted from Antrobus et al.[32]).

These findings underline the potential value of forced desynchrony protocols for investigating circadian factors in dreaming.

Experimental desynchronization of circadian factors

A study[32] using a partial forced desynchrony procedure purported to control both ultradian and circadian components of dreaming. To create a phase delay of dreaming relative to a hypothesized circadian influence, sleep onset and offset were intentionally delayed by 3 h. REM and NREM dreaming thus both occurred 3 h later than usual, i.e. coincident with the rising phase of the circadian influence (see Fig. 4). By comparing REM and NREM dream reports from the phase-delayed condition with control reports from non-delayed sleep, the relative contributions of an ultradian factor (REM vs NREM awakenings) and a circadian factor (Control vs. Delayed sleep) were assessed.

Delayed dream reports were longer and more visually intense, especially when collected later at night. Habitual REM > NREM differences were also demonstrated, but REM and NREM reports were both affected by the circadian factor independent of this stage difference. For visual imagery, the circadian effect size (0.23 or small) was about 30% of the ultradian effect size (0.70 or large). The pattern of results prompted the authors to claim that ultradian and circadian sources of cortical and subcortical activation are independent but additive in their effect on dreaming, as in this study. A subsequent study by the same group[62] found a much larger effect size for the circadian influence (0.51 or very large), even larger than that for the ultradian influence (0.40), and possibly due to the authors' more precise estimation of the circadian nadir in this study. The two influences again were independent and additive in their effects on dreaming. The authors suggest that ultradian and circadian influences may be attributed, in part, to activation in distinctive cortical regions, e.g. left temporal language regions for the circadian factor, a notion consistent with observed patterns of LH and RH processes (see 'Continuity of processes across sleep/wake states' later).

One study described above[18] that employed 20/40m sleep/wake schedules to sample dream content from REM and NREM naps provides even more suggestive experimental evidence that the propensity for dreaming fluctuates with circadian periodicity over 24 h (Fig. 5). Subjective dreaming scores elicited for NREM reports were clearly distributed sinusoidally across the 24-h day, with an acrophase at 08:00. REM report scores were elevated for the entire diurnal period of 06:00–16:00 and then dropped markedly. However, this plateau may indicate that REM dream scores were more likely to reach a ceiling on the four-pt scale assessed. The fact that the curve for NREM dreaming scores parallels exactly the curve for REM sleep (but not NREM sleep) propensity, as measured by time-in-stage prior to awakening (not shown), and that NREM dream duration is highly correlated with average REM sleep duration ($r = 0.87$, $p < 0.0001$), strongly suggests that the propensities for dreaming output from REM and NREM sleep are both influenced by the same underlying circadian oscillator.

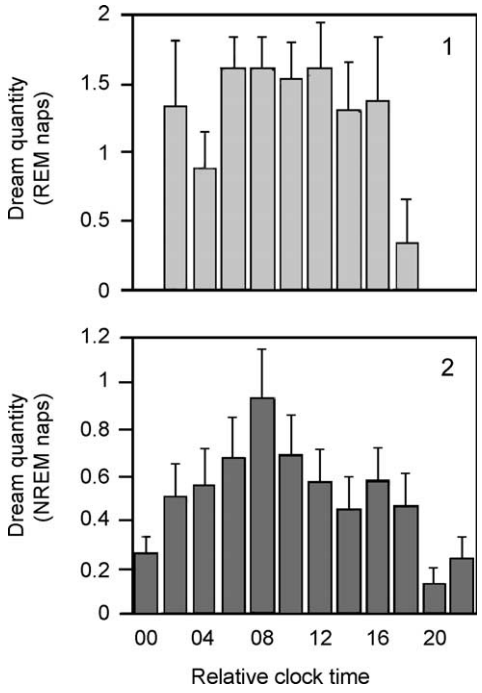

Figure 5 Dreaming scores for subjects on a 20m/40m sleep/wake schedule for three consecutive days with dream sampling at each awakening. Three-day means are displayed by 2-h blocks time-locked to the onset of melatonin release (22:00). Dream scores for NREM reports (panel 2) clearly conform to a circadian oscillation with an acrophase at 08:00 am whereas scores for REM reports (panel 1) remain elevated from 06:00 to 16:00, possibly a ceiling effect for the rating scale used. Interestingly, the NREM dream score peak coincides with the peak of REM (but not NREM) stage duration. A further, circasemidian, component is suggested by the secondary NREM peak at 16:00 (adapted from Suzuki et al.[18]).

Depression

In many depressed patients there may be a disruption of circadian factors affecting the REM-NREM sleep cycle and accompanying dream mentation.[56] For dream content, this disruption is a reversal of the normal increase in DLQ within a night. In one study,[56] all non-depressed subjects

displayed the expected DLQ increase for REM reports but 46% of suicidal subjects displayed a decrease ($p=0.015$) as well as increasing dream dysphoria within the night.

Similarly, studies[63,64] have demonstrated relationships between presleep depressed mood and within-night decreases in negative affect in REM dreams as well as an association between within-night changes in negative affect preponderance (more negative dreams early, fewer later) and remission from depression at one year. While these authors speculate that their depressed patients suffered from a failure of functions regulating mood and integrating affect into memory during sleep, the 'reversed DLQ' and dream negativity patterns may also signal an abnormal phase-advance of circadian processes. Wehr's *internal coincidence* model of depression[65] in fact stipulates that mood in the depressed is affected by a phase-angle discrepancy between a phase-advanced circadian clock and the sleep–wake cycle. Manipulations of the sleep–wake cycle, such as sleep deprivation or phase advance of the sleep period, may alleviate depressive symptoms.[66]

A circadian-based explanation of depression is still contentious and alternative models could account for the changes to dreaming seen in the early part of the night among the depressed. Some alternatives might propose a deficiency in sleep need or 'process S,' as in the *two-process model of sleep regulation*[67] or, even more specifically, a diminution of the 'delta sleep ratio' (quotient of delta power in NREM1 and NREM2.[68]

PTSD

An imbalance of early vs. late sleep like that observed in depression also appears to characterize PTSD; there is an apparent phase advance in dreaming such that vivid nightmares, which in Nightmare Disorder are usually seen in late REM sleep, occur also during the first half of the night[69] and even during NREM sleep.[70] A circadian phase-advance is also suggested by sleep anomalies such as reduced REM latency, increased REM density,[71] circadian phase specific hypocortisolemia[72] and increased autonomic responsivity during both REM and NREM in the first vs. the second half of the night.[73] Together, these findings seem to indicate that the intensification of sleep and dreaming normally ascending later in the night are advanced to the beginning of the night, affecting both dreaming and sleep physiology.

Jet lag

Transmeridian travel may affect dreaming by desynchronizing dream-related circadian processes and sleep time in a manner similar to that described for depression and PTSD. This possibility is consistent with the observation that jet lag produces more frequent sleep paralysis episodes,[74] which usually involve very vivid and frightening dream imagery in the form of hypnagogic hallucinations. Further, the physiological prerequisite for sleep paralysis, sleep onset REM or SOREM, is more probable when REM sleep pressure is elevated, as it may be when the circadian propensity for REM sleep is phase advanced. Thus, the frequency of SOREM, sleep paralysis and intensified frightful dreaming should all be increased immediately after east-to-west transmeridian travel that induces a temporary phase advance of the circadian oscillator. Although research is lacking on this question, the two cases reported by Snyder,[74] who both underwent long transatlantic flights and both experienced anxious, isolated sleep paralysis events, are consistent with this suggestion.

Aging

Evidence that circadian rhythms are phase advanced in older subjects[75] suggests that the circadian-coupled peak in dream intensification might again occur earlier than normal in the sleep episode. This may well explain why there is a resurgence in sleep paralysis events among 40–80-year-olds[76] and a decrease in retrospectively estimated dream recall with advanced age. The latter finding may indicate that the spontaneous morning recall of dreams, on which retrospective recall estimates are probably largely based, is lower because of the circadian phase advance. Differences between young and old subjects in the pattern of dream vividness within a night[5] do provide some evidence for this notion. The pattern of dream vividness for the NREM sleep reports of older subjects consists of an early night peak and a subsequent decrease—a pattern opposite to that of younger subjects and completely consistent with a phase advance.

Continuity of processes across sleep/wake states

Just as the propensity for REM sleep continues into wakefulness,[77] circadian factors affecting dreaming may also continue to affect waking state processes that are functionally related to dreaming. The series of studies by Cohen[57] described above demonstrates differential increases in LH and RH processes across the night, in particular, progressive increases in LH content but no changes in RH content. The pattern suggests that LH processes

may reach an acrophase in the morning, concomitant with REM sleep propensity, while RH processes reach their acrophase only later in the day. In fact, during wakefulness LH processes such as spelling proficiency are relatively more engaged in the early morning[78] whereas RH processes such as consonant-vowel voicings and melodies are more engaged only later in the day.[79] Such phase discrepancies are true of physiological systems more generally, with separate oscillatory control of circadian rhythms in the left and right hemispheres[80] and of different components of sports performance.[81] Thus, although some aspects of dream production, such as overall output of the dream generator, may have a singular circadian oscillator, other, more specific aspects may be modulated by separate circadian oscillators.

Summary

While it is not possible to quantify circadian oscillations on the basis of measures limited to sampling in the nocturnal portion of the sleep/-wake cycle, several lines of research converge to support the suggestion that one or more circadian processes are implicated in dream production. Most evidence for within-night changes in dream recall and quality is consistent with a circadian model; additional evidence complements it by demonstrating (a) a propensity to vivid dreaming in situations of likely circadian phase advance, (b) circadian fluctuation of dream production during ultra-short sleep–wake schedules, and (c) continuity between sleep and wake states on measures of LH and RH processes.

Some of this evidence could be interpreted in the context of alternative, non-oscillator explanations, such as the possibility that dream vividness is an inverse function of sleep propensity across the night. For example, delta EEG power, which is widely used as a marker of sleep propensity, decreases clearly between the first and second NREM periods, but much less so between the second and subsequent NREM periods. Dream vividness changes follow an inverse pattern. However, this alternative, *inverse sleep propensity*, explanation does not easily account for all the experimental and pathophysiological findings reviewed above nor does it parsimoniously explain why the changes in a process tied to NREM sleep should affect dreaming taking place in *both* NREM and REM sleep.

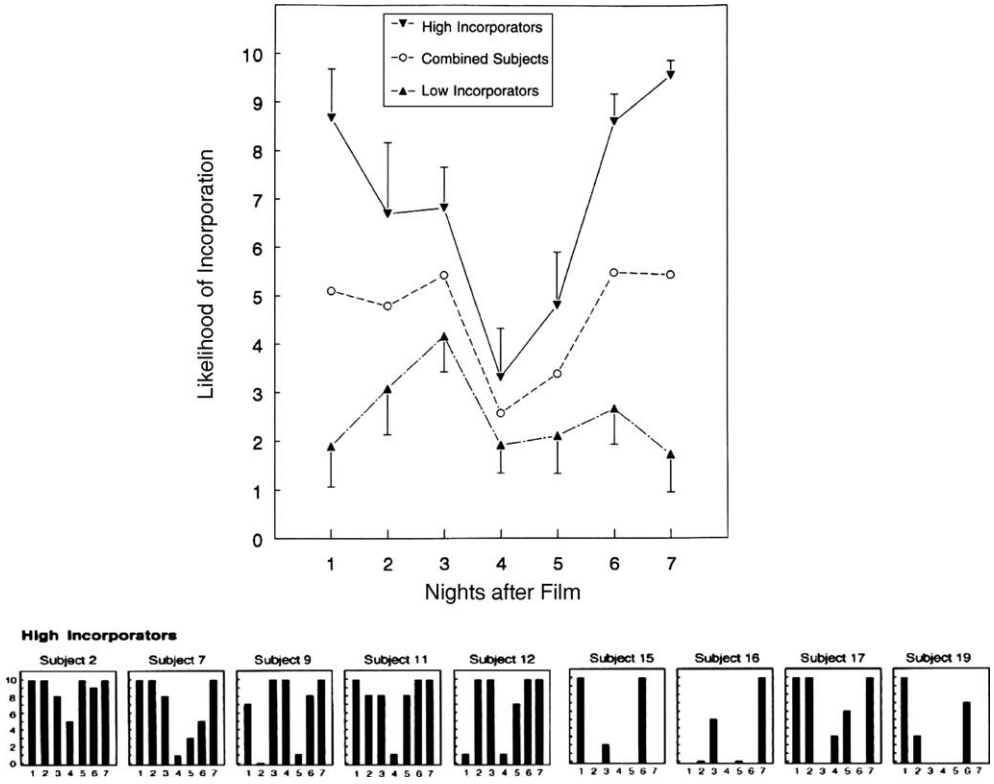

Figure 6 Mean (SEM) ratings of likelihood that film elements were incorporated into dreams for high ($n=9$) and low ($n=10$) incorporating subjects. The U-shaped circaseptan effect is apparent only for high incorporating subjects. Bottom panel illustrates the U-shaped curve for ratings for these nine subjects (from Powell et al.[112]).

Circaseptan rhythms

Accumulating evidence implicates circaseptan interval timers in processes of dream formation. Circaseptan oscillators have been described for biological systems such as heart rate, blood pressure and body weight,[82] for psychopathological symptoms such as the timing of attempted suicides[83] and for cognitive phenomena, such as reaction time,[84] among others. Similarly, circaseptan interval timers that are reactive to endogenous or exogenous events have been identified for adaptive and compensatory responses see,[85] such as post-operative swelling, but also for changes in sleep architecture following learning.[86] To illustrate, Smith and Lapp[86] found that fast- (vs. slow-) learning rats trained on a 2-way shock avoidance task showed increases in REM sleep time and REM sleep density that were highest 6 and 7 days after the start of training, respectively.

No studies have examined changes in dream recall or content across a week, but at least eight studies support the possibility that access to the memory sources contributing to sleep mentation are modulated by circaseptan processes. Six of these studies were conducted by our group using both within- and between-subjects designs (see reviews in Refs. 87,88). In the within-subjects designs, subjects are requested to write out dream reports in home logs for 7–12 days. A traceable memory source, such as a self-reported concern, a disturbing film or an overnight laboratory stay, is evaluated by judges for its degree of correspondence with the dreams. When correspondence ratings are plotted against days prior to the dream, a sinusoidal U-shaped curve is observed, with peak scores occurring for dreams following the source by one day (day-residue effect) and by 6–7 days ('dream-lag' effect; see Fig. 6). The latter is consistent with a circaseptan interval timer.

In the between-subjects design,[87] subjects are randomly distributed into groups and asked to find memory sources for a selected dream on one and only one specific day prior to the dream. They evaluate their degree of certainty of recall and the degree of correspondence between the memory source and the dream. This design again produced a clear U-shaped curve in dream-memory correspondence for subjects who were relatively confident of their recall (see Fig. 7). Randomization and other controls minimize the chance that these effects are attributable to confounding by the seven-day societal schedule, experimenter bias, subject anticipation, etcetera.

Evidence consistent with the previous findings—and thus with a circaseptan influence on dream

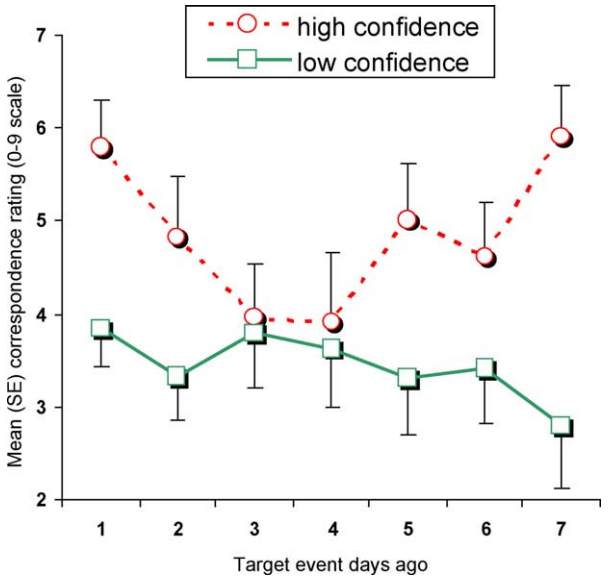

Figure 7 Mean (SEM) ratings of likelihood that prior events correspond to some element of the target dream for each target day for low (green squares) and high (red circles) confidence groups. The typical U-shaped curve is apparent only for the high confidence group (from Nielsen et al.[87]) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

memory sources—was reported by Jouvet[89] in an analysis of 400 of his personal dreams. One analysis of 130 dreams and their correspondences with memory sources revealed a sinusoidal U-shaped curve with peak correspondences occurring for memories one day (34.6%) and nine days (10%) prior to the dream. In a second analysis of 270 dreams recorded during and after travel abroad, memories of spatial elements of the new environments began to appear in recorded dreams on average 7.8 days after leaving on the trip. Similarly, appearances of the new environments ceased on average 6.5 days after returning home. Jouvet suggested that the delayed incorporations into dreams demonstrated a process responsible for spatial memory of environments, a suggestion that we subsequently confirmed.[87]

The 'goggles' study[61] described earlier, in which subjects wore red-tinted lenses for a five-day period, also supports the implication of circaseptan processes in dream memory access. The 'goggle effect' (%dream objects containing red, orange or yellow) was most apparent for the first REM episode of each night and—for the first REM episodes taken together—was sinusoidally distributed over nights in a circaseptan pattern.

Our group also has evidence that the circaseptan pattern of memory access may be implicated in dream function.[87] On the one hand, delayed

incorporations into dreams preferentially treat spatial location[89] relative to immediate incorporations. On the other hand, delayed incorporations are also related to interpersonal problem-solving, specifically, interpersonal relationships ($p=0.001$), positive emotions ($p=0.012$) and resolved problems ($p=0.046$).[87]

Circatrigintan rhythms

The possibility that circatrigintan rhythms influence dreaming is reasonable in light of observed circatrigintan modulation of physiological parameters of the menstrual cycle, including changes in sleep parameters (see review in Ref. 90). The possibility is also consistent with the demonstration of monthly mediation of cognitive and motor abilities, such as implicit memory,[91] articulatory and fine motor skills, and spatial ability.[92] These changes are for the most part linked to circatrigintan oscillations in the hormones estrogen and progesterone (e.g. Ref. 91) and thus we might expect to observe circatrigintan modification of women's dreams in particular.

Changes in dream recall and content have, in fact, been reported for different temporal positions in the menstrual cycle. However, these findings lack consistency and thus provide only marginal support for the notion that dreaming is modulated by monthly rhythms.

Several studies converge in suggesting that dream emotion is modulated on a monthly basis, with an intensification occurring during menses. One early study[93] of 15 women seeking routine gynecological exams (menses vs. mid-cycle) and 15 controls (mid-cycle only) revealed that dreams recalled during menses displayed more expressed emotional conflict than mid-cycle dreams. A second study of four undergraduate students[94] PSG-recorded 1/week for 11 weeks replicated this finding, i.e. manifest sexuality and overt hostility in dreams were both more frequent during menses; further, dream imaginativeness did not vary with menstrual cycle phase. The latter finding for sexual content, but not for hostility, was replicated in a study of two 19-yr-old women's dream reports collected over 12 weeks; hostility in this case was highest in the ovulatory phase.[95] Finally, a study of over 450 dreams from 50 first-year nursing students[96] revealed changes during menses consistent with the prior studies: increased references to blood visible on females, increased aggressions toward males, increased initiation of social interactions of all types (pp. 377–385). Many other changes during the menstrual phase were noted that imply emotional concerns only indirectly or symbolically, e.g. themes of uterine functioning, marriage to strangers, the color red on static objects. Emotional content also varied with personality; women with negative attitudes toward menstruation initiated far more aggressive exchanges with male dream characters during the menstrual phase than did women with positive attitudes.

Such individual differences may help explain why other studies have reported changes with menstrual phase that are not necessarily consistent with the previous findings. Benedek and Rubenstein[97,98] studied dreams from nine psychoanalysis patients sampled in either the ovulatory ($N=75$ cycles) or the menstrual ($N=125$) phases in conjunction with daily measures of temperature, estrogen and progesterone. Dreams with active sexual and libidinal impulses were correlated with preovulatory estrogen dominance whereas dreams with passive receptivity and self-preoccupations were correlated with post-ovulatory progesterone dominance. A reanalysis of these dreams[99] using psycholinguistic content measures revealed a further link between estrogen dominance and an enhanced capacity to retrieve and communicate concrete, specific, and clear dream images. These findings are consistent with a recent study of 16 healthy young women (22.6 ± 2.25 yr, range: 20–28) which found increased erotic content, positive emotions and increased plausibility of imagery in the preovulatory phase and aggressive interactions and negative emotions in the premenstrual phase.[100]

A lack of monthly oscillations has also been reported. A polysomnographic study of 10 healthy women (18–24 yr) with low menstrual distress that assessed anxiety, hostility and sexuality found no changes in dream recall or emotional content across the menstrual cycle.[101] Such inconsistencies among findings suggest caution in drawing conclusions about circatrigintan rhythms in dreaming. Although there may well be relationships between hormonal fluctuations and dream content that parallel relationships between, e.g. estrogen levels and implicit memory[91] or verbal articulation,[92] more carefully controlled studies are needed to clarify whether dream changes are due to biological fluctuations, to concomitant changes in self-perception, stress and mood, to trait personality differences, or to all of these types of factors. A lack of attention to personality factors as well as inconsistency in definitions of menstrual cycle phases are two major methodological problems. Finally, monthly rhythms have not yet been explored in male subjects.

Implications

Taken together, the evidence reviewed is consistent with the assertion that biological rhythms of different types are implicated in the production and recall of dreaming. While other explanations cannot be excluded, there is good reason to seek further clarification of dream-related oscillatory and interval timing processes with more carefully controlled studies. Such clarification may have important consequences for understanding normal dream function, for developing biomarkers of dreaming processes and for explaining dream disturbances. Implications for dream function and biomarkers are discussed further below in an effort to illustrate the range of possible research methods that can be implemented to unearth the chronobiological underpinnings of dreaming.

Dream function

Despite accumulating research supporting a role for sleep in procedural learning (see review in Ref. 102) a clear role for dreaming remains to be demonstrated. In light of evidence that temporal factors are implicated in sleep-mediated learning (for example, Ref. 103), further study of dreaming's modulation by chronobiological features may help to clarify how dreaming facilitates learning and memory functions.

On the one hand, temporal factors in learning are suggested by the identification of learning-sensitive 'windows' at specific times that interact with sleep variables. To illustrate, alcohol results in memory loss for cognitive and motor procedural tasks and a concomitant reduction of REM density in the first half of the night when it is ingested at bedtime but not when it is ingested in the afternoon, immediately after task acquisition.[104]

On the other hand, temporal factors are demonstrated by evidence that sequences of physiological changes during sleep are associated with improvements in performance. For example, improvements in visual discrimination learning are associated with increased amount of both SWS in the first two hours of sleep and REM sleep in the last two hours of sleep.[105] While both of these phenomena seem to indicate that temporally complex physiological sequences underlie simple learning effects, neither excludes the possibility that temporal changes in dreaming, such as those identified in the present review, constitute an integral part of these sequences. There are as yet no findings that directly address this issue.

Implications for biological markers of dreaming

Attempts to identify biological markers of dreaming have had mixed success, perhaps because chronobiological factors have not been systematically considered. It is possible that biological systems vary in their influence on dream content and dream recall as a function of their chronobiological phase. Some relevant findings are available for candidate markers known to vary with circadian periodicity and which therefore merit further study. One, cortisol, shows an abrupt, switch-like increase 2–3 h after sleep onset,[106] i.e. approximately when dream recall and vivification also increase abruptly. Further, cortisol levels are associated with disorders for which the phase of dream intensification appears to be disturbed, i.e. depression[107] and PTSD.[108]

Two other measures, HR and EM density, have been found to be associated with dream recall only at specific times of night. In one of our studies,[51] HR predicted dream recall only from REM2 ($p=0.009$) whereas EM density predicted dream recall from REM3 ($p=0.003$) and marginally from REM4 ($p=0.144$) and REMP 5 ($p=0.102$). In other words, dream recall was best predicted by a physiological system which was at or near its circadian acrophase, i.e. HR early in sleep[109] and EM density in the final third of the sleep period.[110] Associations with EM density are of particular interest because of evidence that modifications in the within-night patterns of EM density are associated with adaptation to severe stress,[111] which is also a proposed function of dreaming.

Implications for chronobiological theories of dreaming

An increasing focus on chronobiological processes in dream production will likely enable development of more sophisticated theoretical models of dreaming. While no comprehensive model will be attempted in the present work, the literature reviewed nevertheless brings to light factors that may constrain such chronobiological models or suggest new directions for their development.

Between-rhythm interactions. An obvious outcome of the present literature review is that dreaming is affected by biorhythms with widely different levels of oscillation or timing, e.g. ultradian, circadian, circaseptan. Chronobiological models of dreaming must address these differing levels of influence. One class of models, which may be termed *activational convergence*

models, stipulates that dreaming processes are affected in a qualitatively identical manner by different levels of oscillation. For example, Antrobus[32] provides evidence that cortical activation is associated with basic dreaming characteristics like increased visual clarity whether this activation is produced by REM sleep or by the rising phase of a circadian process. In a similar manner, Roffwarg[61] demonstrates that a complex interaction between circadian (time of night) and circaseptan (day of week) factors determined the extent of 'red goggle' incorporations into dreams. These convergence models may be contrasted with another class of models, termed *activational divergence models*, which postulate that different levels of oscillatory organization exert qualitatively different influences on dreaming—possibly on different subcomponent processes of dreaming. While no such model has yet been put forward, the present review identifies several results consistent with such divergence. To illustrate, different levels of oscillation have been linked with different types of memory access during dreaming: access to episodic vs. semantic memories is modulated by ultradian clocks, access to temporally recent vs. remote memories by circadian clocks and access to spatial and interpersonal memories by circaseptan clocks.

Within-rhythm interactions. Another outcome of the present review is that variations in dreaming are associated with oscillations occurring within a specific type of biorhythm, e.g. the REM/NREM ultradian rhythm. Chronobiological models of dreaming must account for these variations. One class of models, which may be termed *uni-oscillator models*, stipulate that dreaming is regulated by a single oscillatory process. For example, the ultradian REM/NREM rhythm may be seen to produce fluctuations in all features of dreaming simultaneously. This type of model is supported by the wealth of studies demonstrating parallel changes in a large number of dream content measures either as a function of ultradian variation (REM/NREM differences) or circadian variation (within-night differences). In contrast, a class of models termed *multi-oscillator*, might stipulate that component processes of dreaming are regulated by separate, partially independent, oscillators in a manner similar to the regulation of numerous physiological variables such as temperature, alertness and melatonin under the control of circadian clocks. Some evidence in the present review supports such models as well, e.g. dream content measures whose temporal morphologies are seemingly out of phase with those of other measures—as in the case of content that increases in frequency or intensity between REM3 and REM4, as opposed to between REM1 and REM2 as for most other measures.

Isomorphism. While the problem of bio-cognitive isomorphism is far from resolved, a satisfactory chronobiological model of dreaming will preferably address this problem at some level. Models supporting isomorphism may be of two general types: (1) those postulating isomorphism between dreaming and an underlying biorhythm that is *process non-specific*, e.g. an oscillatory source of activation which leads to fluctuations in the intensity of dreaming in general; (2) those postulating isomorphism that is *process specific*, e.g. an oscillatory process that determines the waxing and waning intensity of a specific dream attribute, such as emotion, self-representation, vestibular sensation or narrative coherence.

Practice points

- A role for chronobiological factors in generating nightmares and other dream disturbances (e.g. sleep paralysis with frightening hypnagogic hallucinations) is feasible. A phase-advance pattern of REM activity and dream intensification has been observed for both depression and post-traumatic stress disorder, suggesting the implication of underlying circadian rhythm disturbances in the dream symptoms accompanying these disorders. Thus, factors producing relative circadian phase-advance, such as timing of melatonin administration, transmeridian travel and shift-work schedules, should be considered as possible sources of nightmares and other disturbing dreams.
- One-week delays in the incorporation into dreams of emotionally salient daytime experiences often obscure some of the sources of disturbing dreams. Practitioners and therapists can help patients uncover the sources of such dreams by directing their search for associations to a temporal window spanning 5–8 days prior to the occurrence of a troubling dream.
- Disturbing dream content may be a function of monthly hormonal fluctuations among women.

Research agenda

Chronobiological dream studies are burdened by methodological difficulties inherent to both domains of research. Evidence that dreaming may be influenced by at least five levels of biorhythmicity indicates that dream collection studies must be carefully controlled in several respects. Chronobiologists have developed effective protocols which can be applied to deal with much of this complexity. Future research should at a minimum attempt to:

- study dreaming using standard chronobiological protocols for human subjects: constant routine, partial forced desynchrony, ultrashort sleep/wake cycles, free-running sleep schedule, sleep interruption protocol.
- assess dream content in relation to validated measures of oscillatory physiological systems: e.g. body temperature, cortisol, melatonin, delta spectral power.
- assess interactive effects on dreaming of different levels of biorhythmic oscillation, e.g. ultradian/circadian, circadian/circaseptan.
- assess dream recall and content in subject populations under controlled conditions of circadian phase advance or delay: e.g. 'morning' vs. 'evening' types, phase-delay

The preceding describes some minimal considerations in the development of chronobiological theories of dreaming; emerging theories will likely combine elements of these different classes of models (see examples in ref. 113). However, as illustrated in the Research agenda, many basic studies still are needed to advance development of such theories. Model-building will both contribute to and benefit from this new research.

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