The Threshold of Sleep: Perception of Sleep as a Function of Time Asleep and Auditory Threshold

Michael H. Bonnet and Sarah E. Moore

V.A. Hospital and Department of Psychology, University of Cincinnati, Cincinnati, Ohio, U.S.A.

Summary: A number of studies have found that many subjects have reported being awake when awakened during various periods of electroencephalographically (EEG)-defined sleep. These observations have led to an examination of the perception of sleep after periods when EEG-defined sleep was experimentally varied between 1 and 140 min. Twelve normal young adult subjects slept in the laboratory for 5 consecutive nights. Each subject was briefly awakened five times on each night, and subjective state, auditory arousal threshold, and sleep/wake time estimation data were collected. The threshold of sleep onset (i.e., the point at which a report of sleep was given 50% of the time) occurred 2–4 min after the first sleep spindle. In contrast, auditory thresholds rose rapidly within 1 min of the first sleep spindle. The threshold data corroborate the appearance of a sleep spindle as an objective measure of sleep onset. However, subjective sleep onset appears to be a relatively lengthy period during which perception of state is blurred and uncertain. Key Words: Sleep onset—Subjective sleep onset—Arousal threshold.

In recent years a growing interest in the relationship between electroencephalographic (EEG) measures and subjective reports of state has developed. Many studies, for example, have reported that insomniacs perceive their sleep latencies as significantly longer than those recorded by use of EEG measures. Other studies (1–5) have indicated that subjects occasionally report being awake when awakened from various stages of sleep. For example, Moore et al. (5) reported that 83% of insomniac and 50% of normal subjects reported being awake when awakened at the initial sleep spindle of the night. Rechtschaffen (2) found that awakenings 10 min after the first sleep spindle resulted in an awake response in 27% of awakenings made from insomniacs and in 4% of awakenings made from normal controls. Webb (1) found that 10% of subjects reaching stage 2 sleep and 5%
of subjects reaching stage 3–4 sleep reported not falling asleep during a 45-min nap period.

While it is clear that there is less than perfect agreement between sleep onset as determined by EEG and sleep onset as determined by subjective response, the relationship between these two variables has not been systematically explored. Additionally, the examination of other physiological or subjective report variables might give a clearer understanding of the sleep onset period.

One variable of interest is auditory threshold because it is (i) easily quantifiable; (ii) presumably based on central processing factors; and (iii) usually measured by a subjective perceptual report (i.e., "I hear it now.") It is well known that auditory thresholds change as a function of sleep stage. Evidence also exists that thresholds vary within a given stage of sleep (6,7). One pre-EEG study has measured auditory thresholds across periods of sleep onset (8). That study described a curve of auditory threshold over the first hour of sleep which was characterized by a 25-min period of gradually rising thresholds, followed by a 25-min plateau, followed by a decrease in thresholds. It is conceivable that these changes in auditory arousal thresholds are more closely linked with subjective perception of state than are EEG measures. On the other hand, the initial description of threshold change during the first 50 min of sleep can be cast in more modern EEG terms as about 5 min of stage 1 sleep, 10 min of stage 2, and 10 min of stages 3–4 (i.e., a period of increasing thresholds as a function of sleep stage changes), followed by a fairly lengthy period of stage 4 (the plateau period). This sleep stage explanation, however, has no empirical basis, and it is not known whether threshold changes accompanying sleep onset are gradual and extended as implied by the early data or are more abrupt and accompany specific EEG changes such as the disappearance of alpha or the appearance of sleep spindles.

It has been reported that individuals may have the ability to subjectively differentiate sleep stages (9,10). The basis for this ability is not clear, but one potential explanation is that the subjective choice was made based upon depth of sleep (i.e., threshold) at awakening or on related changes in mental content. If so, it would imply that perception of stage was directly or indirectly linked with auditory threshold, and that rapid or gradual changes in thresholds across sleep onset periods might be related to similar changes in subjective report of sleep onset. Further, changes in threshold or mental content might have significant influence on other perceptual variables such as the perception of time.

The present study further examined the subjective properties of the sleep onset period. Paired experimental awakenings were made at various inter-awakening intervals, and auditory thresholds and subjective perception of state and time were recorded. We report here changes in auditory threshold and subjective perception as a function of time asleep.

**METHODS**

Twelve young adults (six male and six female) who reported normal sleep and were between the ages of 18 and 28 slept in the laboratory for 5 consecutive nights.
Each subject was scheduled to sleep in the laboratory according to his/her normal hours of sleep with the stipulation that the hours were the same for each night. EEG recordings were made from C3-A2 and O2-A1, and EOG recordings were made from both eyes referenced to A2. Additionally, a hearing aid earphone insert was taped into the preferred ear of the subject at bedtime. For each subject, all threshold measurements were made from the same ear. On each evening a waking threshold measurement was completed at bedtime.

Each subject was awakened five times on each night of the study. The five conditions are listed below.

(i) The first awakening was begun at the appearance of the first well-formed sleep spindle. Throughout this paper, sleep onset is defined as the appearance of the first well-formed sleep spindle 0.5 s or longer as determined, retrospectively, by a well-trained scorer not aware of the conditions of the study.

(ii) The second awakening began at least 2 h after the subject had fallen asleep following the first awakening. This awakening also required that at least 5 min of continuous stage 2 sleep had elapsed before it was initiated.

(iii) The third awakening was begun 0.5, 1.5, 3.5, 7.5, 15.5, or 24.5 min after the subject had fallen asleep following the second awakening.

(iv) The fourth awakening began at least 2 h after the subject had fallen asleep following the third awakening. It also required at least 5 min of continuous stage 2 sleep.

(v) The final awakening was begun 0.5, 1.5, 3.5, 7.5, 15.5, or 24.5 min after the subject had fallen asleep following the fourth awakening.

The subject was awakened on each occasion by an ascending series of 1000-Hz tones, transmitted through the earphone, produced by a Beltone Model 109 screening audiometer. The series was started at 0 dB SPL and increased in 5 dB steps. Tones were presented in a 3-s on, 3-s off series with intensity increased during the off phase until the subject said, "I'm awake." After each awakening, a standard set of questions was read to the subject over the intercom. The questions began with, "Were you asleep or awake right before you heard the tone?" If the subject gave an asleep response, he was asked how long it took to fall asleep and for how long he had slept since last talking to the technician. These two values are referred to as estimated sleep latency and estimated sleep. If the subject gave an awake response, he was asked how long it had been since he had last spoken to the technician. In this case, the estimate given was used for the estimated sleep latency and estimated sleep was defined as zero. The questions lasted approximately 1 min.

Awakenings 3 and 5 were designed to allow 30 s for the threshold procedure and thus to occur at actual intervals of 1, 2, 4, 8, 16, or 25 min after the first sleep spindle. If the subject moved out of stage 2 sleep at any point during the sleep interval, the awakening was made anyway, but the condition was repeated on the next night. The data to be presented for the 1 to 25-min time periods reflect only intervals of exclusively stage 2 sleep. A given subject normally was exposed to three of the intervals after awakening 2 and the other three intervals after awakening 4. The order of the six interval presentations after awakenings 2 and 4 was
randomized for each subject with the constraint that across all subjects, each interval would appear with approximately equal frequency at each point in the series (and thus after awakening 2 or 4) so that time of night could not play a role in the findings. While each subject was exposed to all intervals, subjects were not exposed to each interval at each time of night. The intervals presented on the first night were considered adaptation and were presented again on the fourth or fifth night of the study, depending upon the number of intervals which had to be repeated to insure properly timed awakenings from stage 2 sleep.

Statistical analyses

Nine conditions were identified in the study: the initial sleep onset awakening, awakening 2, awakening 4, and the six intervals (1–25 min). The initial sleep onset condition differed from the others in that it did not follow another awakening and that it always occurred first. Although data from the first awakening appear in the table and figures to be presented, it was not included in any of the analyses. Seven time intervals, including the six 1 to 25-min intervals mentioned above (balanced for time of night across subjects) and 140 min, the average of awakenings 2 and 4 (balanced for time of night by averaging the two values for each subject) were included in the analysis of variance (ANOVA). The ANOVA had terms for intervals of time asleep and subject. To control for the potentially inflated degrees of freedom associated with the repeated measures, F values termed significant in this paper exceeded 4.84, the p < 0.05 F value associated with the Greenhouse–Geisser conservative df of 1 and 11 (11). F values termed questionable were those <4.84 and >2.25 (p < 0.05 with 6 and 60 df).

As a check on questionable results, within-subject linear regressions were also performed on arousal thresholds and time estimates as a function of time asleep. For example, if arousal thresholds increased in a subject when he had been asleep longer, the regression line for that subject would have a positive slope.

RESULTS

Due to the intrinsic difficulty involved in determining an initial sleep spindle as it occurs, and because the time required to complete an awakening with the threshold procedure used in the study varied slightly with each threshold determination (usually being about 1 min), exact timing for the awakenings was not possible. Table 1 presents means for the latency to sleep onset after the previous awakening and the total amount of sleep immediately prior to the awakening. There was no overlap between conditions in terms of total sleep allowed (with the exception of the initial spindle condition, which overlapped both the 1- and 2-min conditions).

The subjective estimates of EEG data were not normally distributed and each

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1 Because subjects were not always in stage 2 sleep 2 h after awakenings 1 and 3, the technician sometimes had to wait until stage 2 sleep appeared and lasted for at least 5 min. For this reason the 2-h interval between awakenings actually averaged out to 140 min and is therefore called the 140-min condition. The data from awakening 2 and awakening 4 were compared by t-test. The only significant differences between variables were in EEG sleep latency following the previous awakening (10.6 and 3.3 min, respectively) and in the estimate of that sleep latency (18.7 and 16.5 min, respectively).
value was therefore transformed to its log value before the ANOVA. Table 1 presents geometric means for these subjective estimates. The estimates generally followed the objective manipulation; that is, estimates of total sleep increased as total sleep increased (average of 12 individual subject correlations \( \rho = 0.71, t_{11} = 9.42, p < 0.0001 \)), and estimates of sleep latency were longer in the conditions with the longer EEG latencies \( \rho = 0.48, t_{11} = 6.43, p < 0.0001 \).

Figure 1 presents percentage of subjects who reported being asleep when awakened. The analysis of variance for report asleep was significant \( F_{6,65} = 5.26 \); and pairwise comparisons indicated that a report of being asleep was more likely at time periods of 16 min or longer than at time periods of 1–8 min. As Fig. 1 indicates there was a clear increase in the percentage reported asleep as a function of total time asleep since last awakening. A 50% report of being asleep was reached about 2–4 min after the initial sleep spindle. The point at which each individual subject changed his report from awake to asleep was found by averaging the length of sleep following the last awake report and the length of sleep following the first sleep report. The median change point across subjects was 3.9 min after sleep onset.

Subject confidence of the sleep/wake rating as a function of time asleep was of questionable significance \( F_{6,65} = 2.61 \). Pairwise comparisons showed that subjects were more confident at 2 and 25 min than they were at 1 min. This pattern of differences suggests that chance variation may have played a role in the finding.

In contrast to the subjective report of being asleep, auditory thresholds increased rapidly at sleep onset (being at 64% of the highest stage 2 value at 1 min after sleep onset). Thresholds then increased relatively slowly as the interval between sleep onset and awakening increased (see Fig. 2). The ANOVA indicated only a questionably significant value for differences between conditions \( F = 2.32 \). Pairwise comparisons indicated that thresholds in the 140-min condition were higher than those in the 1- or 4-min conditions and that thresholds in the 8-
FIG. 1. Plot of percentage of subjects subjectively reporting themselves to be asleep at awakening as a function of time after EEG sleep onset. The open circle corresponds to the initial spindle awakening.

FIG. 2. Plot of auditory arousal threshold level when awake and after various intervals of sleep. The open circle represents the auditory arousal threshold at the initial spindle awakening.
and 16-min conditions were higher than those in the 1-min condition. The marginal increase in threshold as a function of longer intervals asleep suggested that within-subject linear regressions of thresholds across increasing intervals of sleep might have positive slopes. It was found that 11 of the 12 individual subject regressions had a positive slope ($p = 0.0031$, sign test), and this indicated that thresholds did increase significantly as a function of length of stage 2 sleep. Changes in arousal threshold were also significantly correlated within subject with rating of sleep/waking, although with a low correlation ($\rho = 0.29, t_{11} = 5.09, p < 0.001$).

No change was found in waking auditory threshold measured immediately after awakening as a function of length of sleep interval ($F = 1.31$).

**DISCUSSION**

The present experiment has examined auditory threshold and subjective report after various, experimentally controlled intervals of sleep in normal subjects. As expected, the probability of a subjective report of being asleep increased as a function of time asleep. In a classic perceptual sense, the threshold for the experience of an event is the point at which the event is detected 50% of the time (12). As classically defined, therefore, the median threshold of subjective sleep onset was 3.9 min within subjects (i.e., when the sleep intervals at which each subject changed from an awake to an asleep response were averaged) and between 2 and 4 min between subjects (i.e., the interval at which 50% of the subjects claimed to be asleep) after EEG sleep onset. However, threshold by definition implies uncertainty. In the present experiment, certainty of the presence of the state of sleep increased as a function of time asleep; more than 90% of the subjects felt that they were asleep 16 min after EEG sleep onset. These data are consistent with other studies showing that a few subjects may report being awake even after fairly long intervals of sleep (1,2). The decrease in the percentage reported asleep from 100% at 25 min to 84% at 140 min may reflect either (a) that the steady state of perceiving sleep during the night is less than 100% or (b) that the criterion for awakening in this study after 140 min of sleep was less stringent than that in the 25-min condition. The latter could have existed because 25 min of continuous stage 2 sleep was required in the 25-min condition, while the 140-min condition required only 2 h since the prior experimental awakening and 5 min of stage 2.

In contrast to subjective report, auditory threshold increased rapidly near sleep onset and had reached 64% of the maximum value within 1 min of sleep onset. This generality was obvious during data collection. In a given subject, auditory threshold may shift by 60 dB or more in either direction within the space of 6 s, yet a 60-dB increase in threshold might be accompanied by a subjective report of being awake and an admonishment to turn down the unbearably loud tone (which invariably had failed to elicit any response at an intensity.5 dB lower). The threshold data, which were based on the subjective response of the subject, offer a striking contrast to the subjective report of state data. The close agreement of threshold and EEG data, on the other hand, serves as a cross validation of those measures of sleep onset and highlights the fact that a large perceptual
change can occur without subjective awareness that it has occurred. This perceptual shift is reminiscent of the perceptual changes which occur with alcohol ingestion. While no one would believe the subjective report of a drunk driver that he was functioning perfectly, that disbelief apparently has little effect on the perception of the drinker.

The current threshold data are not directly comparable to those reported by Mullin and Kleitman (8) because Mullin and Kleitman did not use either EEG or decibel measures. Nonetheless, the present data do confirm that after sleep onset, there is a small, gradual increase in auditory threshold over the next 8 min. There are several potential reasons why the period of threshold increase in the present study was shorter than that in the earlier study. Mullin and Kleitman collected all of their data either at the beginning of a nap or at the beginning of night sleep. Their period of threshold change could have been longer because their subjects could have easily continued into stage 3–4 sleep (which did not occur in the present study), because they made many arousals during one sleep onset period, or because sleep onset may be more gradual if there has been little or no immediately prior sleep.

An examination of Table 1 shows that the subjects consistently overestimated their sleep latency as compared to their EEG sleep latency. The median overestimate was 5.6 min across conditions. This estimate, independent of the earlier reported subjective perception of sleep/wake, might place subjective sleep onset about 5–6 min after EEG sleep onset and would lend further validation to the initial subjective placement of sleep onset at 2–4 min after EEG sleep onset.

Subjects had difficulty differentiating the short intervals of sleep. Even when reports of being awake were assigned sleep estimates of 0 and when data were normalized by log transforms, the estimated duration of both 1 and 8 min of EEG sleep was 7.1 min in length. It is probable that the lack of ability to estimate sleep intervals of less than 10 min follows directly from uncertainty about the placement of sleep onset itself, which must be seen as a period of some minutes in which perception of state is blurred and shifting. The interpretation is supported by the fact that as intervals of sleep increased beyond 8 min, estimates of time asleep also increased correspondingly.

Many studies (13–21) have reported that normal subjects can accurately estimate their initial sleep onset latency at night. In the present study, the least error in subjective judgment of sleep latency, both in relative and absolute terms, was found after the initial arousal. The size of this error (3.2 min) was small and consistent with objective-subjective values from normal sleepers reported in the other studies. Later overestimates were greater in both relative and absolute amounts. The finding may be explained by the circadian rhythm in time estimation. Estimates (i.e., the ratio of subjective to objective intervals) would be predicted to increase somewhere between the beginning (22) and the middle (23) of the sleep period although the point where time estimations begin to increase cannot be specifically located (24). The three latency ratios with consistent time placement in the present study (initial spindle, awakening 2, and awakening 4) support such a circadian rhythm, with respective ratio values of 1.22, 2.69, and
5.34. This implies that even normal sleepers may perceive awakenings later in the night as longer.

As an alternative to the circadian explanation, it could also be argued that awakenings later in the night were perceived as longer as a function of frustration from repeated awakenings during the night. While this possibility cannot be directly discounted from the present estimation data, no evidence for such an effect could be found on other measures, including EEG latency after awakenings (which decreased across the night). Further, the latency ratios did not change as a function of night in the study (F = 0.63).

The overestimation of latencies after middle-of-the-night awakenings is of interest because it could help explain why people who have frequent awakenings may misperceive their sleep process. If it takes as long as 5 min after the first spindle to perceive the onset of sleep in normal subjects and if circadian effects further increase the estimate, it can be easily seen how a night with many awakenings may be perceived as containing little sleep. In conditions such as nocturnal myoclonus, in which there are periodic arousals, the following events might take place: (a) a myoclonic jerk briefly awakens the individual; (b) within a few seconds sleep spindles reappear in the record and arousal thresholds increase rapidly; (c) 5 min later the individual perceives sleep onset. In reality, of course, the myoclonic jerk is often followed by a second jerk 30 s later—at a time when the EEG indicates sleep and thresholds are rapidly increasing (so that there is no awareness of the jerk per se) but the individual still perceives himself as awake when awakened by the second jerk. If such arousals continued throughout the night, this individual might claim that he never fell asleep.

Data from Moore et al. (5) and Rechtschaffen (2) indicate that the perception of sleep onset differs in insomniacs as compared to normals. Future work must systematically explore the perception of sleep in insomniacs, psychopathological groups, and the elderly.

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REFERENCES


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