AUDITORY THRESHOLDS DURING CONTINUING SLEEP *

Michael H. Bonnet
Sleep Laboratory, Loma Linda VA Hospital, Loma Linda, CA 92357, U.S.A.

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Five subjects were asked to respond to a 1000 Hz tone with a standard button push response during sleep. A method of limits procedure was used to track their auditory thresholds when awake and during various stages of sleep. Subjects adapted to the procedure and were able to make consistent responses while their EEG indicated stage 1 or stage 2 sleep. While the threshold level at which a response was made was directly related to EEG state, there was no significant correlation between the interval between responses and the threshold level. It was concluded that stable auditory thresholds could be obtained during stage 1 and stage 2 sleep after little laboratory adaptation and that this behavioral response could be a useful indicator of central processing ability during sleep.

1. Introduction

Although sleep has generally been considered an absence state, a number of studies have documented several information-processing capabilities which remain (reviewed by Bonnet, 1982). For example, several studies have shown an increased probability of producing a behavioral response to reinforced vs. non-reinforced pure tones or sounds (Williams, Morlock and Morlock, 1966; Zung and Wilson, 1961) or meaningful stimuli such as names (Oswald, Taylor and Treisman, 1960) or the cry of an infant (Poitras, Thorkildsen, Gagnon and Norman, 1973). Another group of studies has shown the ability of sleeping subjects to retain information presented during sleep for a few seconds (Okuma, Nakamura, Hayashi and Fujimori, 1966; Lasaga and Lasaga, 1973; Oltman, Goodenough, Koulack, Maclin, Schroeder and Flannigan, 1977; Shimizu, Takahashi, Sumitsuji, Tanaha, Yoshida and Kaneko, 1977). However, long-term recall for events presented to sleeping subjects has shown chance levels of recall (Simon and Emmons, 1955; Emmons and Simon, 1956).

In most information-processing sleep studies, subjects awake or are awakened to report registration of information. In studies which have incorpo-
rated a large number of simple behavioral responses during sleep, subjects may habituate to signals (Sharpless and Jasper, 1956), show only evoked EEG changes as responses, or sleep through a number of presentations. Granda and Hammock (1961) used this approach by having subjects close a microswitch on a 3-sec schedule during the night to avoid foot shock. They found that the button push behavior could be produced by subjects reliably during all stages of sleep except REM sleep, which was not tested. More recently LaBerge, Nagel, Dement and Zarcone (1981) have reported the ability of lucid dreamers to report when they are dreaming (i.e. in REM sleep) by making a series of stereotypical eye-movement signals. Together, these studies imply the ability to make coherent behavioral responses during sleep, and, at least in some individuals, the ability to monitor and report state within the sleep process.

In a series of studies performed to determine auditory arousal thresholds during sleep as a function of drug use (Bonnet, Webb and Barnard, 1979), level of exercise (Bonnet, 1980) and amount of accrued sleep (Bonnet and Moore, 1982), it was noticed on several occasions during the standard collection of auditory threshold data from subjects who were awake that subjects who drifted off to sleep during the procedure often continued to respond at higher dB levels. The present study sought to extend our knowledge of behavioral responsivenes during sleep by demonstrating the ability of subjects to track their auditory threshold during sleep. Data on threshold levels, EEG indicators, and measure reliability will be presented.

2. Method

Five young adult subjects (four males and one female) between the ages of 18 and 40 agreed to participate. Each subject slept during his/her normal hours of sleep. EEG recordings were made from both eyes referenced to A2 (all sleep parameters defined by Rechtschaffen and Kales, 1968). Subjects additionally had a hearing aid earphone insert taped into their preferred ear at bedtime. For each subject, all threshold measurements were made from the same ear.

The subjects were laboratory personnel who had previously participated in other projects. The major data analyses to be reported are based on the first experimental night for the subjects. Three subjects slept for two additional nights so that the effects of learning/habituation over nights and of longer time series could be examined.

On each evening, standard EEG/EOG calibrations and waking threshold measurement were completed at bedtime by means of a Beltone Model 109 screening audiometer. The series was started, according to sleep criteria to be described, at 0 dB SPL (sound pressure level) and increased in 5 dB steps. Tones were presented in a 3-sec ‘on’, 3-sec ‘off’ series with intensity increased

![Fig. 1](image_url) Three examples of responding in different stages of sleep from a single individual. In each the top line is C3-A2, the second line delimits tone presentation at the dB SPL level designated between the limits. The bottom line is the subject response button. (A) Responses during wakefulness. (B) Responses from a section of record scored as ‘15 sec or less of stage I’. (C) Responses from a period of continuing stage 2.
while the audiometer was not producing a tone ("off"), until the subject responded by pushing the button taped into his/hand.

During each night each subject had 5 series of tone presentations. The first series began about 30 min after sleep onset, and the series were separated by an hour of sleep. Each series lasted between 20 min and 60 min, although most were close to 20 min. Rare, longer series were interjected on later lab nights to look for long-term habituation effects. The series began from stage 2, 3, 4 or REM, although it was not possible to initiate a series from each stage on each night. During each series, if the subject did not respond by pressing the response button taped into his/her hand, the intensity of the 1000 Hz tone was increased by 5 dB on the next presentation. If the subject did respond, then the intensity of the tone was decreased by 5 dB on the next presentation, in a classic method of limits threshold approach (Underwood, 1966). For example, a brief excerpt of tone intensities from a given series might be 0 dB, 5 dB, 10 dB*, 5 dB, 10 dB, 15 dB*, 10 dB*, 5 dB. The "*" indicates a subject response at the indicated intensity. This methodology allowed E to continuously "track" threshold. The initial response in each series was analyzed separately. Thereafter, the following definitions were used:

Interval length — Time in seconds between subject responses. This parameter varied by the mechanism of tone production from 3 sec (response to 2 consecutive tones) to 120 sec (time to reach maximum audiometer setting in a 5 dB steps).

Threshold — The dB SPL setting of the audiometer when a response was produced. Rare responses when the audiometer was off were not scored.

Ongoing EEG — Standard sleep criteria were used to classify EEG between responses. Amounts of alpha, stage 1, and stage 2 were determined for each interval and paired with the following response value for data analysis. The 6 EEG classifications which were chosen were: Alpha during interval (stage W); 15 sec or less of stage 1 sleep (not followed by spindles or K-complexes); stage 1 with 15 sec or less of stage 2 throughout (onset defined as a spindle or K-complex); stage 1 with more than 15 sec of stage 2; stage 2 throughout the interval. Examples of stage W, 15 sec or less of stage 1 and stage 2 from one subject can be seen in fig. 1.

3. Results

Between 105 and 150 scoreable responses were obtained from each subject night. They were categorized by the ongoing EEG between responses. The frequency of each type of EEG response across subjects can be seen in table 1. The frequency of the various EEG responses was relatively equal. However, it can be seen that the great majority of responses were followed by a stage 1 EEG at least briefly. Within this design it was not possible for subjects to maintain stage 3, 4, or REM sleep for more than a few seconds. Each subject had between 14 and 47 examples of each of the 6 defined EEG response categories scored during their sleep. To accommodate the repeated measures analysis of variance (ANOVA), the first 14 observations from each subject from each EEG category were used in the initial analyses. This rule also resulted in data being used exclusively from the first Laboratory night in these analyses.

The first analysis examined the dB level at which a response was made following each of the EEG patterns described. The ANOVA performed had terms for EEG pattern (5 df), replications (13 df), interaction (65 df) and error (336 df). The main effect F-value for EEG pattern was 61.6. This F-value was significant, both with the 5 and 336 df implied by the analysis (p < 0.001) and with Geisser-Greenhouse conservative df of 1 and 4 (p < 0.005). Mean threshold values can be found in table 1. The greater than 15 sec stage 1 condition thresholds were lower than the 15 + sec of stage 2 conditions. The less than 15 sec of stage 2 condition resulted in lower values than the only stage 2 condition.

A similar analysis was performed on interval length. Interval length increased across conditions (F = 93.73; p < 0.001 with 1.4 df). Response—response intervals were shortest when subjects were awake (see table 1) and increased in the sleep conditions. Intervals were obviously longer in those conditions which required more than 15 sec of stage 1 or 2 sleep to be considered.

Measure reliability was determined by intraclass correlation techniques (Guilford, 1954) based on the mean squares within persons over 14 responses.
and the mean squares between the 5 subjects. Reliability for the group of responses was determined for each EEG stage. For the entire group of 14 responses, measure reliability was 0.98 or 0.99 in all EEG conditions. From these levels, measure/measure correlations ranged from 0.76 to 0.91.

The stability of the obtained threshold values was also examined by correlating the length of various sleep stages between responses with the following response threshold. Response–response interval ranged between 6 and 135 sec with the great majority being between 12 and 20 sec. Correlations for amount of stage 1 and stage 2 were performed within subjects over all available responses. None of the individual subject correlations was significant ($p < 0.05$). When combined across subjects, there was also no significant correlation between seconds spent in stage 1 or stage 2 and response threshold (respective average $r$ values were $-0.06$ and $0.23$).

Response series were initiated from stage 2 (16 trials from all 5 subjects), REM (8 trials from 4 subjects) and stage 4 (14 trials from 3 subjects). In all cases initial responses were followed by brief arousal and return to stage 1 or stage 2 sleep. As would be expected from previous research, initial arousal threshold varied as a function of sleep stage (stage 2 = 68 dB; REM = 38 dB; stage 4 = 85 dB). However, the stage in which the series was initiated seemed to have little effect on thresholds recorded after the series had been initiated (i.e. thresholds were in the 60 dB range regardless of initial sleep stage).

The response threshold measure, when controlled for sleep stage preceding, appeared to remain stable across nights in those subjects with multiple observations. The two most frequent responses (stage 1 with 15 sec or less of stage 2 and stage 1 with 15 sec or more stage 2) were examined. Across the three nights, the median response level per series decreased 0 dB and 7 dB respectively in the conditions. Similarly, no systematic change in threshold was seen in the 60-min series versus the 20-min series.

4. Discussion

The present study has documented the fact that reliable auditory threshold measurements can be obtained from sleeping subjects in stage 1 and stage 2 sleep with relatively little pre-adaptation. The threshold levels obtained are clearly different as a function EEG state. Threshold values obtained from continuing stage 2 sleep were of the same magnitude as those obtained upon initial arousal from stage 2 sleep (69 vs. 68 dB) in spite of the fact that they were obtained on occasion within 12 sec of a previous response. Increasing the interval of continuous stage 2 sleep was non-significantly correlated with the following response threshold. Waking level thresholds were almost always obtained when intervals were filled with alpha. The appearance of stage 1 EEG for even 2–3 sec was usually accompanied by a rapid threshold increase (5 to 43 dB). Periods of stage 1 greater than 15 sec or the appearance of stage 2 EEG tended to be related to increasingly higher response threshold.

Several investigators have shown the ability of sleeping subjects to respond under various paradigms while remaining asleep (Granda and Hammock, 1961; LaBerge et al. 1981; Oswald et al.; 1960) While Granda and Hammock (1961) reported that their subjects continued to produce behavioral responses into stage 3 and stage 4 sleep and LaBerge et al. (1981) reported the ability of lucid dreamers to make eye movement signals during REM sleep, subjects in the current study were unable to respond and continue responding in either REM or stage 3/4 sleep. Granda and Hammock (1961) may have been more successful in producing responses from deep sleep, either because their subjects were sleep deprived or because they demanded a larger total number of responses than the present study. A combination of these factors and longer adaptation to the surroundings might result in a much larger proportion of slow wave sleep responses.

The present data affirm the ability of sleeping subjects to make instrumental responses. The large and consistent threshold elevations found indicate the existence of profound inhibitory central nervous system effects operating extremely rapidly at sleep onset and independently of the arousal response; that is, early responses were often accompanied by awakening, but the length of these awakenings decreased rapidly (Sharpless and Jasper, 1956) while thresholds associated with given EEG patterns remained relatively consistent. These inhibitory effects also seem to operate relatively independently from subjective report of state. Bonnet and Moore (1982) have shown that 50% of normal subjects are still liable to believe that they are awake after as much as 4 min of stage 2 sleep. Subjects in the current experiment typically described themselves as 'awake' or 'drifting' throughout the 20 min response series even while displaying rapid threshold shifts.

Subjects in the current experiment did not experience significant habituation or learning effects across nights as is common in other studies of threshold during sleep (Bonnet and Kutz, 1982; Watson and Rechtschaffen, 1969). This study differs from the others in that: (1) An awakening was not required; and (2) a very large number of responses was made as compared to earlier studies. These two factors, as shown by Sharpless and Jasper (1956), probably resulted in rapid habituation of EEG responses (controlled for here by sorting responses into EEG categories) and little learning.

The ability to track auditory threshold in sleeping individuals offers valuable methodology to researchers examining the effects of various manipulations such as drug use, age, sleep pathology (etc) on the sleep process.

References


