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EEG, Consciousness, and Sleep

Charles W. Simon and William H. Emmons

Since the discovery of brain waves, considerable effort has been made to link this physiological activity to psychological correlates. After more than a quarter of a century of research, this hope has been only partially realized. Although clinicians and neurologists have found the EEG useful as a diagnostic tool, its contribution to the psychologist working with normal individuals has been slight (*1*).

The state of wakefulness and sleep of a normal individual, however, has been related successfully to changes in the EEG (*2*). A number of investigators have found that varying depths of sleep, as measured by the length or intensity of tones required to awaken the subject, are related to increases in amplitude and decreases in frequencies of delta-type (*3*) electroencephalographic patterns. When subjects were awake, alpha rhythms (*4*) could generally be detected (*5, 6*).

This article relates specific EEG patterns along the continuum between waking and deep sleep with more complex behaviors associated with degrees of consciousness and unconsciousness. It would be foolish to belabor a precise definition of consciousness. Two measures that are believed to be highly correlated with the "degree of consciousness" in normal and motivated individuals are (i) the ability to recognize and report the occurrence of particular stimuli to which they have been instructed to attend and (ii) the ability to remember and later recall these stimuli.

Consciousness refers to stages of the waking state during which degrees of awareness of external stimuli occur and to the transition state during which internal stimuli—that is, dreams—occur and are recalled. Unconsciousness refers to the state in which various stages of sleep occur. This article emphasizes the investigation of the waking end of the continuum.

Dr. Simon is a member of the technical staff of Hughes Weapon Systems Development Laboratories, Culver City, Calif., and Mr. Emmmons is associated with the RAND Corporation, Santa Monica, Calif.

Materials and Methods

Twenty-one normal, adult male subjects were selected on the basis of IQ (average or above) and a monopolar, occipital EEG showing a continuous alpha rhythm when they were awake and resting with their eyes closed (*7*).

Subjects were pretested to see whether they knew the answers to 96 factual questions on history, sports, science, and the like. They then retired to soundproof, air-conditioned booths for a normal 8-hour night's sleep. The same questions along with the correct answers were played one at a time at 5-minute intervals during the night. Continuously throughout this entire period, monopolar electroencephalographic recordings were made from each subject's right occiput and vertex. A pen marker showed the exact sections of electroencephalographic record during which the questions and the answers occurred.

Subjects were asked to call out their names immediately if they heard the answer to any question. After the 8-hour training period, all subjects were awakened and given the questions again and were tested to determine which of the answers not known previously could now be recalled.

Alpha as an Index of Consciousness

The positive relation between alpha and consciousness has been noted by a number of investigators (*5, 6*). In the present experiment, the period between awakefulness and sleep was extended sufficiently to provide a means of studying the relationship between the quantity and quality of alpha and variations in consciousness, as measured by responding and recalling.

Figure 1 shows sample EEG patterns from the right occiput along with their corresponding measures of consciousness. The letters assigned to the sleep levels correspond quite closely to those used by other investigators (*6*). Figure 1 illustrates that as the quality and quantity of alpha increases, so does the probability that a stimulus will be reported heard when it occurs and correctly recalled later.

Within level O, a slight reduction in the amplitude of the continuous waking alpha before going to sleep and after awakening from sleep was related to a similar decrease in the probability that an appropriate response would be made. As the percentage of alpha continues to decrease in quantity and amplitude in levels A+ and A, there is a corresponding decrease in the probability of responding or recalling. As the individual becomes very drowsy and level A− patterns are observed, the cyclical activity still remains, although it is approximately 2 cycles per second slower than the subject's normal waking alpha rhythm. These waves fall within the alpha frequencies, and recall still has a relatively low probability of occurrence, as does an immediate response.

For the sake of completeness, the obvious should be emphasized. Lack of alpha does not guarantee lack of consciousness. Alpha may disappear during excitement or when concentration takes place (*8*). Furthermore, many normal individuals show little or no observable waking alpha rhythm. Therefore, although alpha may be used to identify consciousness, lack of consciousness, or unconsciousness, must be identified in some other manner.

Delta as an Index of Unconsciousness

In Fig. 2 are shown electroencephalographic patterns—the delta waves—associated with sleep or unconsciousness. No alpha activity was observed within 30 seconds on either side of the answer period. In all levels when this delta activity predominated, subjects neither responded to nor recalled material presented to them; subjects were unconscious and asleep when the patterns in Fig. 2 were observed (*9*).

Stimulus Effects

Unlike the EEG patterns shown in Figs. 1 and 2, approximately 14 percent of the patterns showed marked alterations following the onset of stimulation. Therefore, when we were searching for the presence of alpha frequencies, the record up to 30 seconds on either side of the answer period was included.

In Fig. 3, EEG patterns showing the effects of auditory stimulation on records from both the occiput and the vertex are presented, along with the percentage of items reported heard and correctly recalled when these patterns occurred. From Fig. 3 it can be seen that (i) the ability of subjects to recall and to give immediate responses corresponds to the quality and quantity of alpha frequencies in the vicinity of stimulation and (ii) when alpha and delta frequencies are mixed, the probability of recall is related to whichever of these components predominates. These relations between consciousness and the EEG correspond to those observed with patterns showing no stimulus effects.

In levels A+, A−, and B the alpha frequencies predominated, and the subjects were able to respond and recall to some degree. In levels C and D, the delta waves predominated, and neither criteria of consciousness occurred. In the two placements used, alpha activity is more evident in the occipital tracings, while delta is more prevalent in the vertex recordings.

With pattern *AbA*, the continuous alpha rhythm was blocked at the onset of stimulation only to return when stimulation stopped. This is the classical alpha block (*10*) which differs from the condition where the absence of alpha is associated with deeper drowsy stages in that the disappearance of alpha coincides with stimulation. Pattern *bA* illustrates the situation in which the stimulation is followed by the subject's rapid awakening. With presence of the waking alpha rhythm immediately after stimulation, recall still occurs about 50 percent of the time (*11*). Recall decreases in pattern *A* when stimulation causes a recurrence of alpha but of mixed frequencies between 8 and 12 cycles per second of poorer quality than the waking alpha rhythm.

The percentage of responses drops still further in pattern *Ab* when the subject wakens to the question but falls back to sleep. Alpha is seen only prior to the period when the answer is given.

In the lower section of Fig. 3, the delta waves predominate in patterns *Ds* and *D*. Their amplitude increasing during stimulation. Some of these patterns have been described as K-complexers (*12*). No recalling or responding occurred to items presented at these times.

In the borderline patterns *A/d* and *A/D*, stimulation led to a mixture of alpha and delta. These followed the principle stated earlier; that is, when alpha and delta were mixed, the probability of recall was related to whichever frequencies predominated.

The one exception to the alpha-delta principle occurred with pattern *X* when the stimulus affected the null state patterns of level B. Probability of recall

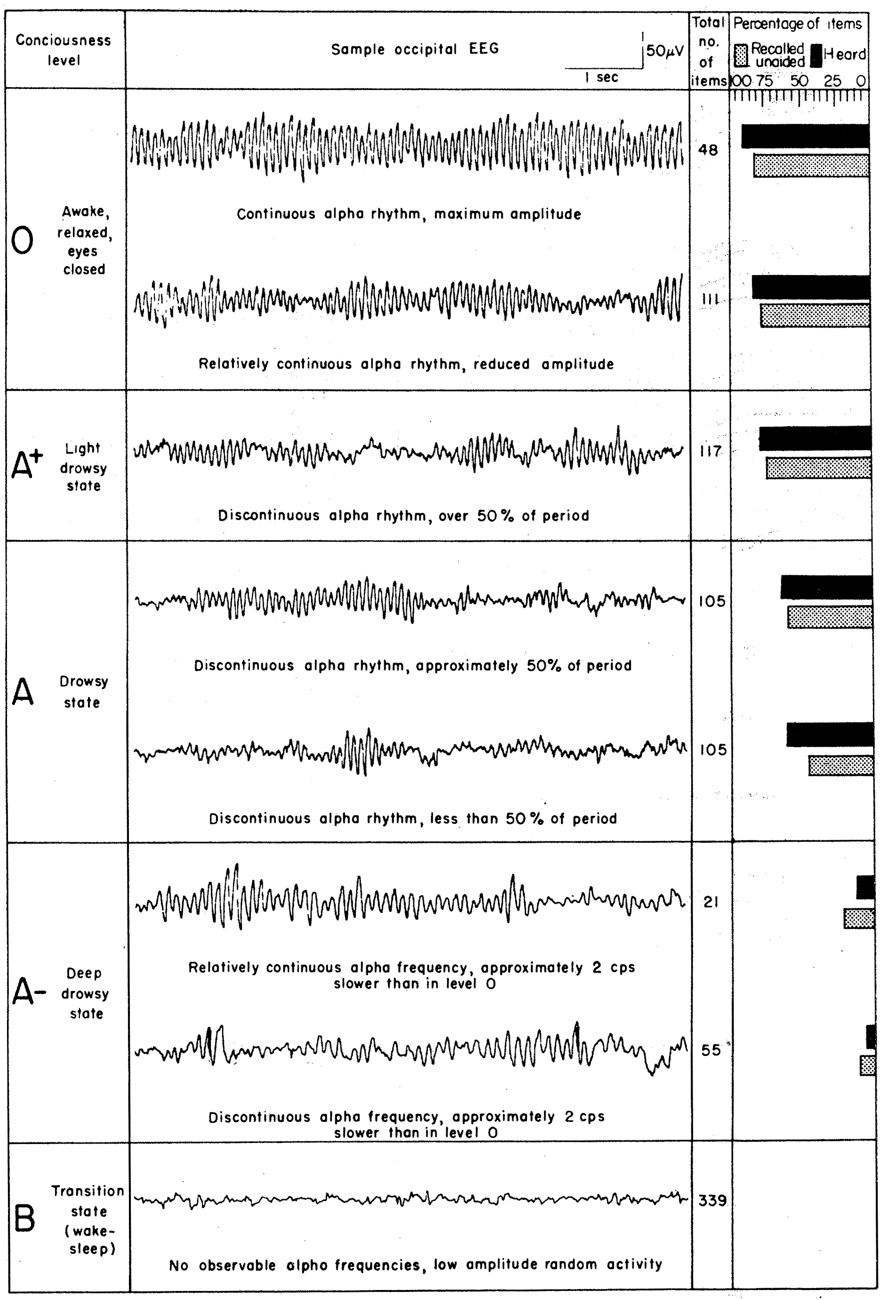

Fig. 1. Percentage of items heard and recalled during the appearance of waking electroencephalograms.

and responses was equivalent to the mixed-wave patterns, although no alpha or delta frequencies were observed; this particular pattern has been associated by other researchers with arousal (*13*).

It should be pointed out that these different patterns did not always occur alone. In fact, when they occurred at all, they generally appeared sequentially as the subject was roused by the stimulation from sleep to wakefulness. At times they would begin when the question was given; at times, when the answer was given. The order of appearances of these patterns corresponded to the shift from the bottom of Fig. 3 upward. Although the order was always the same, patterns were often skipped, apparently depending on the speed at which awakening occurred.

Inertia Effect of Sleep

It has been shown how the quantity and quality of alpha in a short record reflects the conscious state of the individual, and the presence of delta indicates his unconscious state. To what extent does the fact that the subject was awake or asleep sometime prior to the stimulus period have an effect on his ability to respond or recall?

Table 1 shows the percentage of immediate responses and the subsequent correct recalls that occurred at any sleep level when the sleep level during a 60-second period *5 minutes previously* contained or failed to contain alpha frequencies. Both responding and recalling were hindered when the preceding period showed no alpha frequencies and were favored when alpha frequencies were present. These differences are statistically significant ($p < .05$) when a chi-square test was applied to the combined data; the only exception was level 0, "Items reported heard" ($p < .20$).

The foregoing results led to the formulation of the "inertia effect" principle. This principle states: During the presence of any waking EEG pattern, subjects who have recently been asleep tend to show a lower probability of responding or recalling than those who have been awake previously.

Alpha, Movement, and Consciousness

Can the movement of a subject during sleep be used as a criterion of conscious-

Table 1. Immediate responses and subsequent recalls with and without alpha frequencies during a 60-second EEG record 5 minutes earlier.

Current sleep level	Items reported heard (%)		Items recalled correctly (%)	
	Alpha present	No alpha	Alpha present	No alpha
O	89	70	84	27
A+	83	58	79	38
A	72	43	59	42
A−	43	26	40	19
B	10	2	8	3

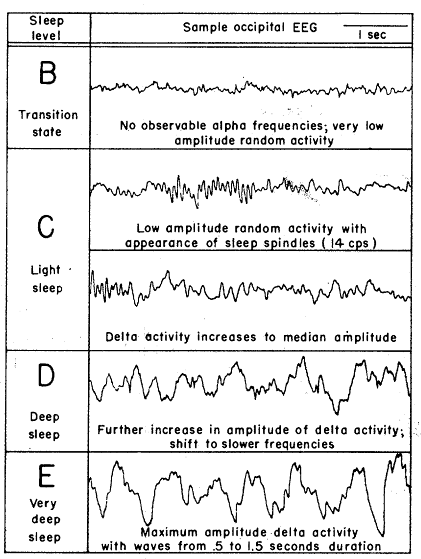

Fig. 2. Electroencephalographic patterns during sleep.

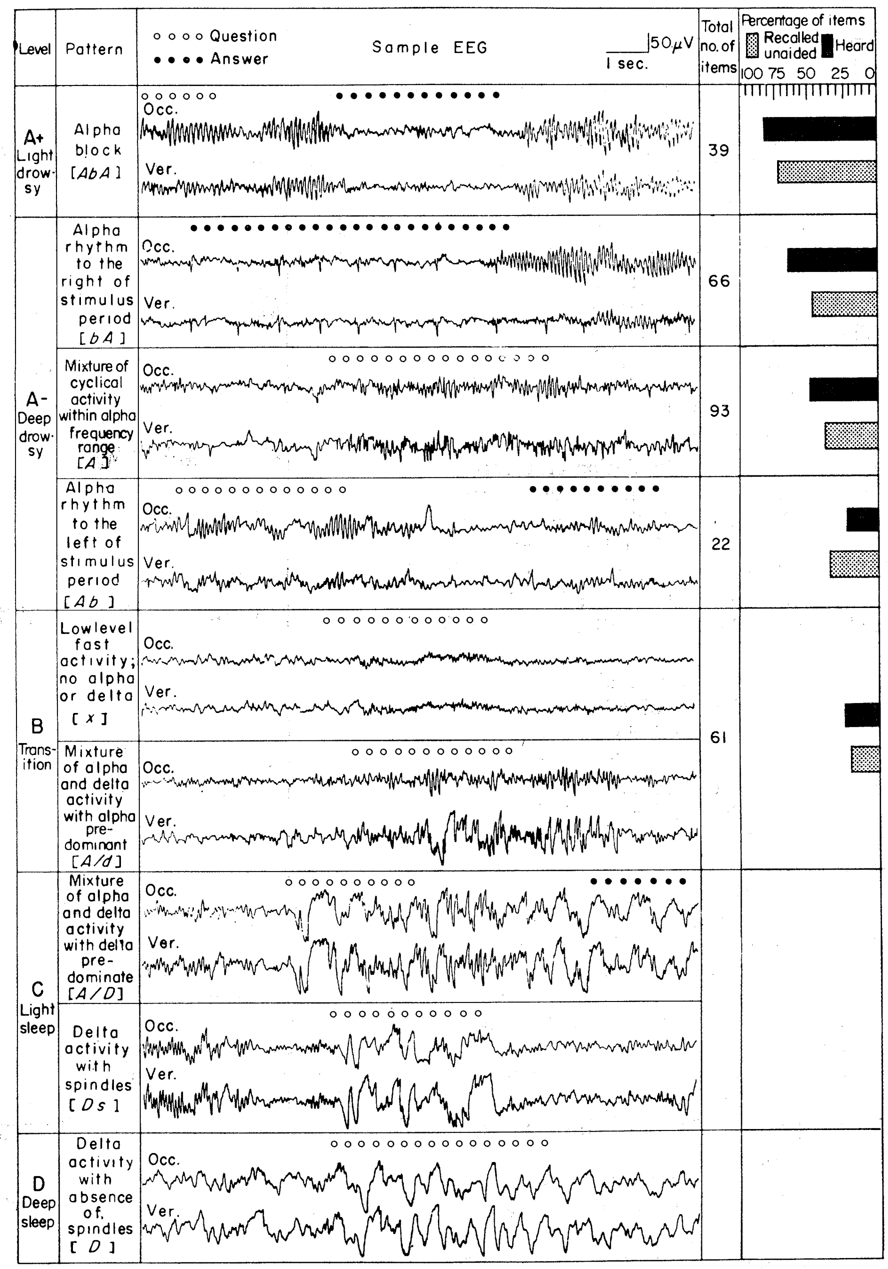

Fig. 3. Percentage of items heard and recalled during the appearance of electroencephalographic patterns modified by stimulation.

ness? What is the relation between alpha, movement, and consciousness as measured by immediate responses and subsequent recall? Table 2 shows the percentage reported heard and the percentage recalled of items that occurred during movements. Since cortical potentials were partially or completely obscured by movement artifacts, it was impossible to assign these items to specific sleep levels. However, the presence or absence of alpha in the vicinity could be detected. When alpha rhythms were found during or at the end of the movement, hearing and recalling tended to be high; when no alpha was observed, subjects heard and recalled practically nothing. These results corresponded with those of alpha and nonalpha periods without movement. Thus, two conclusions can be drawn: (i) it is possible to have movement without the apparent presence of the waking alpha; (ii) the presence of alpha and not movement is the critical criterion for conscious responses.

Table 2. Items heard and recalled with and without movement and alpha frequencies.

	Reported heard (%)		Recalled correctly (%)	
	Alpha	Nonalpha	Alpha	Nonalpha
Move	57	8	35	2
No movement*	63	3	56	3

* Where cortical patterns were not obscured by movement artifacts, the alpha category corresponds to levels O, A +, A, A − and the nonalpha category to levels B, C, D, and E, including all stimulus effects.

Application

A systematic change has been found in the electroencephalographic patterns of alpha-dominated subjects as they go from a state of relaxed wakefulness to deep sleep.

The relation of alpha to wakefulness and delta to sleep and the probability of responding and recalling only when alpha is present negates popular contentions that learning during sleep is possible. This psychological problem has been discussed more thoroughly in other papers (7, 9, 14).

One important practical application of the information in this paper is in the study of factors affecting sleep and rest. In addition to the more classical measure of time (or length of sleep), electroencephalographic patterns can provide a means of continuously measuring depth of sleep without disturbing the subject. Using a two-dimensional measure—length and depth—is a more sophisticated approach to certain problems of sleep and rest and can be expected to yield more satisfactory conclusions. Such problems have important implications for both military and civilian use.

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F. Soddy, Interpreter of Atomic Structure

Frederick Soddy is best known as Ernest Rutherford's young coworker at McGill University at the beginning of this century, when the disintegration theory of radioactivity was put forward, and as the young lecturer at Glasgow who saw most clearly that the heaviest chemical elements have isotopes. Some who knew him in his later life knew him only as one who held heterodox views on economics and politics and as a "crank" on the subject of monetary policy. Those who knew him personally knew him as a fine specimen of English manhood, a good husband, a generous helper of those less well off than himself, a lover of truth (including unpleasant truth) with an original outlook on many of life's problems. He was too shy or too aloof to shine in society and much too earnest and serious minded to suffer anything approaching a fool gladly.

In appearance Soddy was a fairhaired, 6-foot Saxon type with a fine head and regular features. His voice was high-pitched and very southern English in accent. He was born on the south coast at Eastbourne in 1877, went to an English public school there and then to Oxford, where he graduated with first-class honors in chemistry in 1898, thence to McGill till 1902. After a year in London with Sir William Ramsay (during which time he showed that Rutherford's alpha particle from radium was an atom of helium) he became a lecturer at Glasgow, where he remained for 10 years till he became a professor at Aberdeen. In 1919, World War I being over, he went to Oxford as a professor and remained there till 1936, retiring at 59 to Brighton on the south coast 15 miles from where he was born. And there he died and was buried last September.

It was Soddy's misfortune that he never had a wide circle of friends among his fellow-scientists or was *persona grata* with the large staff of fellows and lecturers in chemistry at Oxford. If blame