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Topographical Characteristics and Principal Component Structure of the Hypnagogic EEG

Hideki Tanaka, Mitsuo Hayashi and Tadao Hori

Department of Behavioral Sciences, Faculty of Integrated Arts and Sciences, Hiroshima University, Higashi-Hiroshima, Japan

Summary: The purpose of the present study was to identify the dominant topographic components of electroencephalographs (EEG) and their behavior during the waking–sleeping transition period. Somnography of nocturnal sleep was recorded on 10 male subjects. Each recording, from "lights-off" to 5 minutes after the appearance of the first sleep spindle, was analyzed. The typical EEG patterns during hypnagogic period were classified into nine EEG stages. Topographic maps demonstrated that the dominant areas of alpha-band activity moved from the posterior areas to anterior areas along the midline of the scalp. In delta-, theta-, and sigma-band activities, the differences of EEG amplitude between the focus areas (the dominant areas) and the surrounding areas increased as a function of EEG stage. To identify the dominant topographic components, a principal component analysis was carried out on a 12-channel EEG data set for each of six frequency bands. The dominant areas of alpha 2- (9.6–11.4 Hz) and alpha 3- (11.6–13.4 Hz) band activities moved from the posterior to anterior areas, respectively. The distribution of alpha 2-band activity on the scalp clearly changed just after EEG stage 3 (alpha intermittent, <50%). On the other hand, alpha 3-band activity became dominant in anterior areas after the appearance of vertex sharp-wave bursts (EEG stage 7). For the sigma band, the amplitude of extensive areas from the frontal pole to the parietal showed a rapid rise after the onset of stage 7 (the appearance of vertex sharp-wave bursts). Based on the results, sleep onset process probably started before the onset of sleep stage 1 in standard criteria. On the other hand, the basic sleep process may start before the onset of sleep stage 2 or the manually scored spindles. **Key Words:** Power spectra—EEG stages—Hypnagogic period—Principal component analysis—Topographic maps.

The hypnagogic period is one of the most interesting states for behavioral scientists to classify into discrete levels of wakefulness, drowsiness, and sleep. Various psychological and physiological phenomena occur in the drowsy interval between waking and sleeping. In the present paper, the term "hypnagogic state" is used to refer to the transition period from waking to sleeping, when some or all of these phenomena occur conjointly.

Ogilvie and colleagues (1–3) reported that lengthening response time and intermittent response failure started at standard sleep stage 1 (4). These studies suggest that the behavioral sleep process may start in the period of sleep stage 1. Ogilvie and Wilkinson (1) introduced the concept of a sleep onset period (SOP), defined as the transition between relaxed, drowsy wakefulness and unresponsive sleep. So while the SOP may have sleep stage 1 at its center, it clearly overlaps into stage W and sleep stage 2 as scored by standard criteria (4). Additionally, Hori et al. (5) examined the spatiotemporal behavior of electroencephalogram (EEG) activity in the hypnagogic state using topographic mapping derived from 12-channel EEGs. They reported that the EEG structures of the hypnagogic state were not uniform across the scalp areas and that the hypnagogic state probably started before the onset of sleep stage 1 and continued for a few minutes after the onset of sleep stage 2.

On the other hand, studies in which ERPs (event-related potentials) were employed also suggested that the transition from wake to sleep was a gradual process; the change from wakefulness to sleep did not occur at a single point in time. Näätänen and Picton (6) and Campbell et al. (7) reported that the amplitude of N1 and P300 of ERP would be expected to decrease as the level of arousal dropped. Noldy et al. (8) and Broughton (9) hypothesized that increases in the N2 amplitude would accompany behavioral sleep. Additionally, Ogilvie et al. (10) indicated that response cessation and abrupt increases in EEG power and amplitudes of ERP components converged to allow the re-

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Address correspondence and requests for reprints to Tadao Hori, Ph.D., Department of Behavioral Sciences, Faculty of Integrated Arts and Sciences, Hiroshima University, Kagamiyama 1-7-1, Higashi-Hiroshima 739, Japan.

searcher to identify the "point" of sleep onset more clearly than ever before. Precisely when responding ceases, EEG power increases across all frequencies, and these changes are accompanied by significant alternations in the nature of the ERP; namely, sharp increases in P1, N2, N3, and P3 amplitude take place. Their data also show that changes in N1 and P300 amplitude take place before sleep onset, with both N1 and P300 amplitudes decreasing as response latencies increase significantly. Recently, Harsh et al. (11) reported pronounced changes in P300 during the wake/sleep transition. The latency of P300 increased during stage 1A (alpha waves present during 50–80% of the epoch), and the amplitude was substantially smaller in stage 1B (sleep stage 1). Some ERP components are more or less fully determined by the nature of the stimulus and therefore are exogenous; others, in wakefulness, relate mainly to the level of attention (i.e. component N1), vigilance (N2, P3), or signal detection functions (P3) and so are considered endogenous (9). However, the N2 component has consistently shown an abrupt increase in amplitude around the time of sleep onset (8,10). The P3 component is of particular interest in relation to meaningful information processing during sleep (9).

The results of studies employing ERP indicate the presence of components increasing in amplitude during sleep, although the subject becomes less attentive toward the external stimulus. These findings suggest that the functions of the attention mechanism during waking differ from those during sleep. The decreases of N1 and P300 components, which reflect the reduction of the attention function of the waking system, continue into sleep stage 1. The increases of P1, N2, N3, and P3 components, which reflect the development of the attention functions of the sleep system, start at sleep stage 1.

Standard sleep criteria (4) have been established, and most of the hypnagogic EEG changes are in standard sleep stage 1. Foulkes and Vogel (12) observed that dreamlike hypnagogic reports occurred even during the presleep awake period with an EEG alpha rhythm. Their observations suggested that the onset of the hypnagogic period might precede stage 1 onset [as identified by the modified version of Dement and Kleitman's (13) criteria]. Furthermore, sleep spindles or standard sleep stage 2 have long been used as an objective marker of "true" sleep (14). However, even in this stage, discrepancies appear between subjective reports and polygraphic recordings (15,16), in which a low proportion of asleep judgments were reported early in sleep stage 2 (first sleep spindle). These studies suggest that the hypnagogic effects on the subjective process probably continue after sleep stage 2 onset.

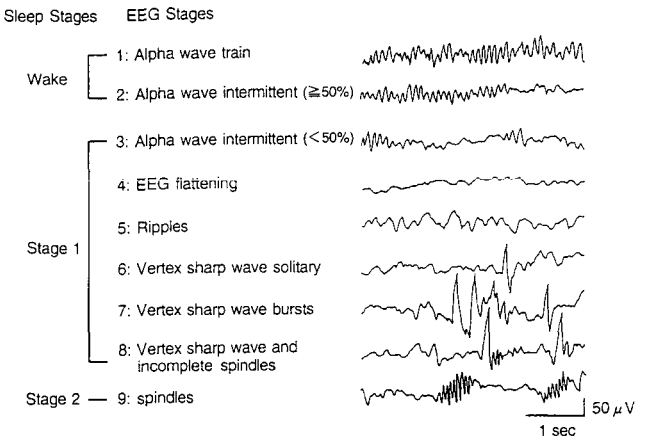

FIG. 1. Typical electroencephalogram (EEG) patterns during the hypnagogic state [following Hori et al. (18)]. EEG stage 1, alpha wave train; EEG stage 2, alpha wave intermittent A ($\alpha \geq 50\%$); EEG stage 3, alpha wave intermittent B ($\alpha < 50\%$); EEG stage 4, EEG flattening; EEG stage 5, ripples; EEG stage 6, vertex sharp wave solitary; EEG stage 7, vertex sharp-wave train or burst; EEG stage 8, vertex sharp wave and incomplete spindle; EEG stage 9, spindles.

The above observations suggest that the hypnagogic state is neurophysiologically and psychophysiologically complex and even paradoxical and that the standard sleep stage criteria, especially for sleep stage 1, are too vague to define when the convergence of behavioral, subjective, and polygraphical measures in the hypnagogic state is being studied.

Therefore, to examine the variations of hypnagogic EEG in detail, the typical EEG patterns during the waking–sleeping transition period were classified into nine EEG stages as shown in Fig. 1 (17,18). These patterns were similar to those described by Shiotsuki et al. (19), which were a revision of the Gibbs and Gibbs' atlas (20). On the other hand, the studies (18,21) that examined the topographical behavior of EEG activity in the hypnagogic state indicated that the topograms were useful in illustrating the characteristics of EEG changes, as noted by early investigators in qualitative EEG studies (12,13,20,22). A quantitative EEG study employing full scalp electrodes is necessary to investigate the topographical EEG features and to obtain the most detailed description of the EEG events during the hypnagogic period. The examination of the inter-regional relationships for each of the dominant EEG frequency band activities and identification of the dominant topographic components may provide a more concise understanding of the structural laws of complicated spatiotemporal changes of EEG activity in the hypnagogic state.

The purposes of the present study were: 1) to evaluate the topographical changes of EEG during the waking–sleeping transition period quantitatively and 2) to identify the dominant topographic components

and examine the regional differences of EEG activity as a function of EEG stage.

METHODS

Subjects

Ten healthy males subjects, who were unpaid volunteers, participated in the study. Their ages ranged from 20 to 25 years (mean, 22.6 years). They were undergraduate students and graduate students of a course in human behavior at Hiroshima University. Each subject was given a detailed description and demonstration of the procedure and apparatus involved in the study before signing a consent form. Subjects were instructed to refrain from alcohol and drugs for 24 hours prior to the experimental session and not to drink any caffeinated beverage on the day of the study. All of the present subjects had previously been adapted to the recording chamber. The waking EEG record for each subject was visually examined for alpha activity (8–13 Hz EEG activity with an amplitude $\geq$20 μV). The subjects with <50% of their waking record occupied by alpha waves were classified as low-alpha subjects. The subjects with $\geq$80% waking alpha times were classified as high-alpha subjects. The remaining subjects, whose alpha times varied from 50% to 80%, were classified as intermediate-alpha subjects. All subjects in this study were high-alpha subjects with alpha times $\geq$90%.

Apparatus

All electrophysiological parameters were recorded simultaneously on an 18-channel EEG (Model 1A97, NEC San-Ei, Tokyo, Japan) and a 14-channel FM tape recorder (SR-50, TEAC Corporation, Tokyo, Japan). The international 10/20 system was used for electrode placement on the 12 scalp sites: Fp_1, Fp_2, F_7, F_8, Fz, C_3, C_4, Pz, T_5, T_6, O_1, and O_2. The EEG ran at a paper speed of 10 mm/second. The EEG data were recorded by FM tape recorder at a tape speed of 12 mm/second. A signal processor (Model 7T18A, NEC San-Ei, Tokyo, Japan) was used for the subsequent off-line analysis of EEG data. The sleeper's room was a 3-m $\times$ 3-m electrically-shielded, sound-attenuated, and air-conditioned bedroom. Temperature readings taken throughout the study showed a mean of 22.5 $\pm$ 1.0°C.

Procedure

Subjects were asked to arrive at the sleep laboratory 2 hours before their usual bedtime. After changing into their night clothes, electrodes were applied. Sleep monitoring varied slightly from that described by Rechtschaffen and Kales (4). Surface electrodes were placed on 12 scalp areas of the international 10/20 system referenced to ipsilateral ear lobes (EEG), two horizontal electrooculograms (EOG), each referenced to ipsilateral ear lobes for slow eye movement (τ = 3.2 seconds), on the chin [mentalis, electromyogram (EMG)] referenced to each other, and on the forehead for the body ground. All electrophysiological parameters were recorded using silver–silver chloride disk electrodes filled with electrode cream and attached with either surgical tape or collodion (scalp placements). Interelectrode impedance was below 5 kΩ. The EEGs were amplified using a high-cut filter setting of 120 Hz and a time constant of 0.3 seconds.

The subjects were instructed to fall asleep after the light was turned off. An experimenter awakened subjects 5 minutes after the appearance of the first sleep spindle by calling his name via intercom before entering the room. Presleep and postsleep questionnaires were used to screen for unusual events that might be expected to influence sleep parameters.

Criteria of hypnagogic EEG stages

According to the criteria of Hori et al. (18), the nine EEG stages of hypnagogic EEG were defined as follows (see Fig. 1). Each recording from lights-off to 5 minutes after the appearance of the first sleep spindle was analyzed. Electroencephalogram stages were also manually scored for each 30-second period of the C_3 EEG record.

EEG stage 1. Alpha wave train: Epoch composed of a train of alpha activity with a minimum amplitude of 20 μV.

EEG stage 2. Alpha wave intermittent (A): Epoch composed of a train with >50% alpha activity with a minimum amplitude of 20 μV.

EEG stage 3. Alpha wave intermittent (B): Epoch composed of a train with <50% alpha activity with a minimum amplitude of 20 μV.

EEG stage 4. EEG flattening: Epoch composed of suppressed waves <20 μV.

EEG stage 5. Ripples: Epoch composed of low-voltage theta wave- (20 μV < θ < 50 μV) burst suppression without a vertex sharp wave.

EEG stage 6. Vertex sharp wave solitary: Epoch containing one well-defined vertex sharp wave.

EEG stage 7. Vertex sharp-wave train or burst: Epoch containing at least two well-defined vertex sharp waves.

EEG stage 8. Vertex sharp wave and incomplete spindle: Epoch containing at least one well-defined vertex sharp wave and one incomplete spindle (duration <0.5 seconds, amplitude <20 μV, >10 μV).

EEG stage 9. Spindles: Epoch containing at least

one well-defined spindle with at least 0.5 seconds duration and 20 μV amplitude.

EEG stages 1 and 2 correspond to stage W in standard criteria (4), EEG stages 3–8 correspond to sleep stage 1, and EEG stage 9 corresponds to sleep stage 2.

Each record was scored entirely by one scorer and was rescored by an independent scorer. A comparison was then made between the two scorings on an epoch-by-epoch basis to determine between-scorer reliability. The reliability score exceeded 90% for each subject's record.

EEG analysis

The polygraphic data were stored on magnetic tape for later off-line analysis using an NEC San-Ei 7T18A signal processor with an A/D converter sampled at 5-second windows of continuous EEG activity from lights-off to 5 minutes after the onset of standard sleep stage 2. The A/D conversion had a sampling rate of 4.88 mseconds per point; a total of 1,024 samples were taken during each 5-second sweep. The power spectra with 0.2 Hz resolution were computed using a Fast Fourier transform and smoothed with a Hanning window. To reduce error variance, the 30-second-long spectra were obtained by averaging six consecutive 5-second epochs. Averaging six consecutive epochs (30 seconds) yielded a magnitude spectrum in microvolts from 2.0 Hz to 14.8 Hz. The average amplitudes of delta (2.0–3.4 Hz), theta (3.6–7.4 Hz), alpha 1 (7.6–9.4 Hz), alpha 2 (9.6–11.4 Hz), alpha 3 (11.6–13.4 Hz), and sigma (13.0–14.8 Hz) were computed from 12 EEG channels. The delta- and theta-band activities were chosen to examine the activities of slow-wave activity in the hypnagogic state. The alpha 1-, 2-, and 3-band activities were chosen to examine the awake-alpha activities. The alpha 3 band was also chosen to examine the slow component of sleep spindles (5). The sigma-band activity was chosen to examine the 14-Hz sleep spindle activity. Since the amplitude of activities above 15 Hz is rather low to quantify the topographical variation, a mapping and statistical analysis of beta-band activities were not carried out. Topography maps from consecutive EEG samples of 30-second epochs for each of the six frequency bands were computed from 12 EEG electrode placements for each of the nine EEG stages. Each topography map was sliced in 10 equal steps of amplitude. The amplitude is shown in 1/1.9 scale for delta- and theta-band activities and 1/1.6 scale for alpha-band activity. Artefacts were screened by visual inspection and rejection decisions were made blindly with respect to subject and EEG stage. Eye blink artefact and vertical EOG appeared at the frontal pole channels (Fp_1, Fp_2); therefore, the epochs with eye blink artefact or vertical eye movements were rejected referenced by the derivations $Fp_1 - A_1$ and $Fp_2 - A_2$.

TABLE 1. *Average time of EEG stages (N = 10)*

EEG Stage	Mean[a]		
	AT	ST	%
1	2.0 (0.2)	1.2 (0.1)	60.0
2	2.4 (0.4)	2.1 (0.4)	87.5
3	1.6 (0.3)	1.3 (0.2)	81.3
4	0.9 (0.1)	0.8 (0.1)	88.9
5	1.4 (0.2)	1.3 (0.3)	92.9
6	0.9 (0.2)	0.8 (0.2)	88.9
7	1.5 (0.4)	1.1 (0.2)	73.3
8	1.3 (0.1)	1.1 (0.1)	84.6
9	4.4 (0.5)	2.6 (0.2)	59.1
Total	16.4 (0.7)	12.3 (0.7)	75.0

EEG, electroencephalogram; AT, the appearance time of EEG stages in minutes; ST, the sampled time in minutes; %, the sampled percentage.

[a] Figures in parentheses show the standard errors.

Statistical analysis

For statistical purpose, amplitude (square root of power) data were log transformed (23,24) to obtain approximation to a normal distribution. Principal component analysis (PCA) was used to extract the dominant topographic components for each of six EEG band activities.

The PCA was applied on the data sets (12 EEG sites × 9 stages × 10 subjects) for each band, respectively. A 12 × 12 correlation coefficient matrix was computed, and principal components were extracted from this matrix. Factors with eigenvalues larger than 1.0 were computed until the cumulative eigenvalues were ≥85.0% of the total variance. A criterion for a loading being more than ±0.7 was used as the level of factor loading significance. The results of PCA were rotated by the normal varimax method into a simple structure. Principal component scores were computed for each band and each EEG stage to examine the regional differences in EEG stage variation.

For each analysis of variance (ANOVA), the significance level was determined following the adjusted Greenhouse–Geisser (25) approach for repeated observations. As the post hoc test, all comparisons between individual cell means were performed using the Newman–Keuls procedure (25) and were based on a 0.05 level of confidence.

RESULTS

Topographic characteristics of the hypnagogic EEG stages

Table 1 shows the average time of EEG stages for ten subjects: 1) the appearance time of EEG stages in

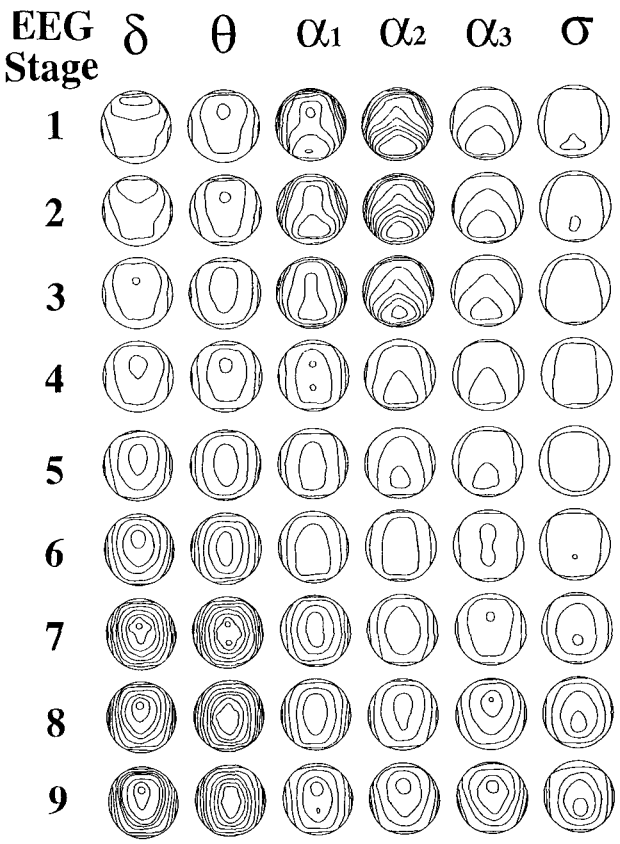

FIG. 2. Average topographic maps for six electroencephalogram (EEG) frequency bands corresponding to nine EEG stages. The upper side of each map shows the nasal side and the lower side shows the occipital side. The numerals on the left side of this panel indicate the nine EEG stages. Each topography map was sliced in 10 equal steps of amplitude. (delta, 1 step = 1.9 μV; theta, 1 step = 1.6 μV; alpha 1, 2, 3, and sigma, 1 step = 1.0 μV).

minutes (AT), 2) the sampled time in minutes (ST; artefact-free data of AT), and 3) the sampled percentage (%) of total appearance time for the nine EEG stages during the waking–sleeping transition period. All subjects showed all stages in the present study, while three male subjects (3/23: 13.0%) lacked EEG stage 4 in the previous study (26).

Figure 2 shows the averaged topography maps of all ten subjects for six frequency bands corresponding to nine EEG stages. The parieto-occipital dominant alpha 2 activity during the waking state (EEG stages 1 and 2) decreased remarkably at EEG stages 4 and 5. Subsequently, the power of alpha 2-band activity increased gradually in the frontal areas from EEG stage 7. The alpha 3 activity had a maximum in EEG stages 8 and 9. Referring to visual inspection, the alpha 3 activity in EEG stages 8 and 9 corresponded to the presence of a 12-Hz slow spindle. On the other hand, sigma-band activity did not show any remarkable changes from EEG stage 1 to EEG stage 5. After EEG stage 6, the dominant focus of this activity, however, appeared in the parietal region, and the power increased sharply in EEG stage 8. The temporal and spatial behavior of this focus corresponded to the presence of a 14-Hz sleep spindle. These regional differences between two types of sleep spindles are particularly clear on topographic maps. The dominant areas of slow-wave activities (both delta- and theta-band activities) were observed first on the frontal (Fz) region and then extended across the scalp from the central to the temporal region as a function of EEG stage. Additionally, theta-band activity showed a dominant pattern in the frontoparietal region beginning in EEG stage 7 (vertex sharp-wave bursts).

To summarize the results, topographic maps demonstrated that the dominant areas of alpha-band activity moved from the posterior areas to the anterior areas along the midline of the scalp. On the other hand, the dominant areas of delta-, theta-, and sigma-band activities did not move on the scalp during the hypnagogic period. In the latter three frequency bands, the differences of EEG activities between the focus and surrounding areas increased as a function of EEG stage.

Principal component structure of the hypnagogic EEG

The EEG topographic maps for each band demonstrated that the scalp distribution of EEG actvities in the sleep onset period were composed of two dominant components. Accordingly, PCA was carried out to identify the dominant topographic components for each of six EEG band activities statistically.

Table 2 displays factor loadings for six frequency bands. Factor loadings of principal components (PCs) refer to the correlation between the PCs and EEG measures. The sites that showed factor loadings above 0.7 (which account for >50% of the total variance) are underlined. The PCA revealed two dominant components for delta-, alpha 2-, alpha 3-, and sigma-band activities. For delta-band activity, the first component (PC1) was closely related to the anterior areas (Fp_1, Fp_2, F_7, F_8, and Fz), while the second component (PC2) was related to the posterior areas (Pz, T_5, T_6, O_1, and O_2). For alpha 2- and alpha 3-band activities, PC1 was closely related to the anterior areas (Fp_1, Fp_2, F_7, F_8, Fz, C_3, and C_4), and PC2 was related to the posterior areas (Pz, T_5, T_6, O_1, and O_2). For sigma-band activity, PC1 was closely related to the anterior–central areas (Fp_1, Fp_2, F_7, F_8, Fz, C_3, C_4, and Pz), and PC2 was related to the posterior areas (T_5, T_6, O_1, and O_2). On the other hand, PC1 for theta- and for alpha 1-band activities showed higher factor loadings in all regions. These components can be explained by the size factor for each band, which reflects the general increases of amplitude all over the scalp.

Principal component scores were computed for each

TABLE 2. *Factor loadings for six frequency bands (n = 10)*

Frequency		Factor loading: Electrode sites Fp_1	Fp_2	F_7	F_8	Fz	C_3	C_4	Pz	T_5	T_6	O_1	O_2	R^2(%)
Delta	PC1	0.93	0.89	0.84	0.88	0.74	0.65	0.67	0.57	0.36	0.26	0.39	0.28	50.2
	PC2	0.26	0.25	0.43	0.36	0.52	0.66	0.60	0.78	0.88	0.92	0.87	0.89	49.8
Theta	PC1	0.92	0.91	0.93	0.91	0.93	0.94	0.93	0.95	0.95	0.92	0.94	0.92	86.4
Alpha 1	PC1	0.98	0.98	0.96	0.97	0.94	0.93	0.90	0.95	0.93	0.92	0.92	0.92	88.4
Alpha 2	PC1	0.90	0.89	0.86	0.88	0.93	0.78	0.78	0.57	0.47	0.35	0.36	0.34	55.2
	PC2	0.37	0.39	0.39	0.41	0.29	0.55	0.55	0.71	0.83	0.89	0.92	0.92	44.8
Alpha 3	PC1	0.98	0.97	0.95	0.93	0.98	0.82	0.90	0.58	0.16	0.23	0.01	0.04	59.7
	PC2	0.09	0.08	0.11	0.07	0.08	0.46	0.35	0.70	0.93	0.88	0.98	0.97	40.3
Sigma	PC1	0.90	0.84	0.83	0.79	0.95	0.86	0.88	0.81	0.34	0.42	0.26	0.31	60.9
	PC2	0.25	0.35	0.29	0.39	0.20	0.39	0.39	0.47	0.87	0.81	0.93	0.90	39.1

PC1, the first principal component; PC2, the second principal component.

band and for each EEG stage to examine the regional differences of EEG stage variations.

Figures 3 and 4 show the average profiles of PC scores for each EEG stage (left) and topographic maps (right) for factor-loading patterns for each band activity. The solid line showing the >0.7 level of factor loading in the topographic maps shows the subgroups extracted by PCA to be the dominant topographic components.

Delta-band activity

The dominant frequency component extracted as PC1 was closely related to the anterior areas for delta. The other lower amplitude component was extracted as PC2. Regarding the variations of EEG stages, the PC scores of both PC1 and PC2 increased sharply from EEG stage 6, while the development of the activity of posterior areas became remarkable after EEG stage 7. The ANOVA (EEG stages × regional subgroups: PC1, PC2) yielded a main effect for EEG stages (F = 84.20, df = 3, 30, ϵ = 0.42, $p < 0.01$) and the interaction between EEG stages and regional subgroups (F = 3.57, df = 3, 30, ϵ = 0.42, $p < 0.05$). The result of post hoc testing revealed three groups among EEG stages [i.e. (stages 1 ~ 5) < (stage 6) < (stages 7 ~ 9)] for both regional subgroups. On the other hand, significant regional differences were obtained in EEG stage 1 (PC-1 < PC-2) and in EEG stage 7 (PC-1 > PC-2) but not in other EEG stages.

Theta-band activity

This band activity showed a single-factor structure, and the PC scores increased from EEG stage 3 to EEG stage 8 as a function of EEG stage. The ANOVA indicated a main effect for EEG stages (F = 29.47, df = 2, 20, ϵ = 0.28, $p < 0.01$). Post hoc testing revealed three stage groups among EEG stages [i.e. (stages 1 ~ 5) < (stage 6) < (stages 7 ~ 9)].

Alpha 1-band activity

This band activity also showed a single-factor structure, but the pattern of fluctuation of EEG stages differed from that of theta-band activity. In short, the PC scores showed higher values in EEG stages 1 and 2, but the scores decreased until EEG stage 5, and after EEG stage 6 the scores returned to the level of EEG stage 3. The ANOVA indicated a main effect for EEG stages (F = 9.15, df = 1, 11, ϵ = 0.16, $p < 0.01$). Post hoc testing revealed two groups among EEG stages [i.e. (stages 1 and 2) > (stages 3 ~ 9)].

Alpha 2-band activity

For this band activity, two regional subgroups were identified. One was in the anterior areas from the frontal pole to the central, and the other was in the posterior areas from the parietal region to the occipital. Each two components showed higher scores during waking, but these scores decreased until EEG stage 6 as a function of EEG stages and increased again from EEG stage 7. The ANOVA yielded a main effect for EEG stages (F = 24.02, df = 2, 17, ϵ = 0.24, $p < 0.01$) and the interaction between EEG stages and regional subgroups (F = 10.55, df = 2, 17, ϵ = 0.24, $p < 0.01$). The results of post hoc testing revealed four groups among EEG stages [i.e. (stages 1 and 2) > (stage 3) > (stages 4 ~ 7) < (stages 8 and 9)] for the anterior areas. For the posterior areas, post hoc testing revealed three groups among EEG stages [i.e. (stages

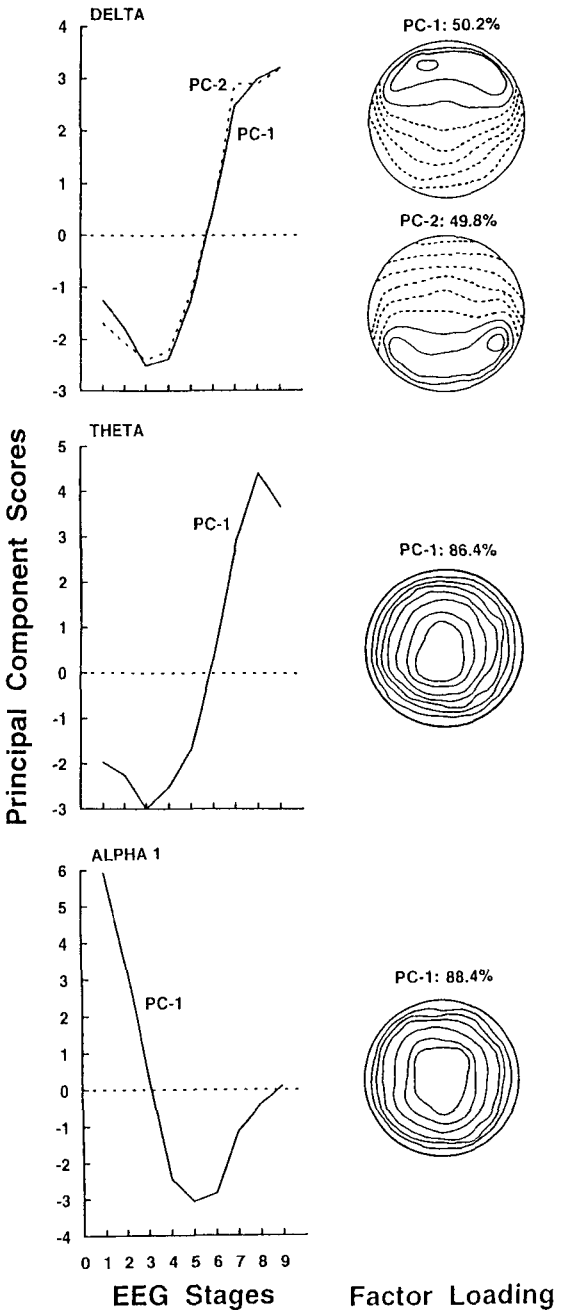

FIG. 3. Variations in averaged component scores for each electroencephalogram (EEG) stage (left three panels). Comparisons of topographic maps for factor-loading patterns for delta, theta, and alpha 1 bands are provided in the three panels to the right. The solid line showing the >0.7 level of factor loading in the topographic maps shows the subgroups extracted by principal component analysis (PCA) to be the dominant topographic component.

1 and 2) > (stage 3) > (stages 4 ~ 9)]. These results indicate that this activity band could be used as a good indicator to discriminate the waking stages. On the other hand, significant regional effects were obtained. The scores of PC2 (posterior area) were higher than PC1 (anterior areas) in EEG stages 1 and 2; on the other hand, PC1 (anterior areas) scores were higher than those of PC2 (posterior areas) in EEG stages 8 and 9. This indicates that the dominant area of alpha 2-band activity moved from the posterior to the anterior areas during the process of sleep onset.

Alpha 3-band activity

Principal components consist of the anterior areas and the posterior areas and correspond to the topographical maps. The activity of PC1 (anterior areas) was dominant during waking, while the activity of PC2 (posterior areas) became dominant from EEG stage 7. The ANOVA yielded a main effect for EEG stages (F = 16.88, df = 3, 31, ϵ = 0.43, $p < 0.01$) and an interaction between EEG stages and regional subgroups (F = 9.88, df = 3, 31, ϵ = 0.43, $p < 0.01$). The results of post hoc testing revealed three groups among EEG stages [i.e. (stages 1 ~ 7) < (stage 8) < (stage 9)] for the anterior areas. For the posterior areas, post hoc testing revealed three groups among EEG stages [i.e. (stages 1 ~ 3) > (stages 4 ~ 7) < (stages 8 and 9)]. On the other hand, significant region effects between anterior and posterior areas were obtained. The scores of PC2 (posterior areas) were higher than those of PC1 (anterior areas) in EEG stages 1, 2, and 3, while the scores of PC1 (anterior areas) were higher than those of PC2 (posterior areas) in EEG stages 8 and 9. These results indicate that the activities in the posterior areas (PC2) reflect the alpha-band activity during the waking stage, while the activities in the anterior areas (PC1) reflect the development of the 12-Hz slow spindle activity.

Sigma-band activity

This band activity was divided into two regional subgroups. The first principal component was extracted from the frontal to the parietal areas. The other lower amplitude group was extracted as PC2. Both component scores of PC1 and PC2 increased sharply from EEG stage 7. The ANOVA yielded a main effect for EEG stages (F = 25.98, df = 3, 24, ϵ = 0.33, $p < 0.01$) and for the interaction between EEG stages and regional subgroups (F = 27.37, df = 3, 24, ϵ = 0.33, $p < 0.01$). The results of post hoc testing revealed significant regional effects. The scores of PC2 (posterior areas) were higher than those of PC1 (anterior areas) in EEG stages 1 ~ 4, and the scores of PC1 (anterior areas) were higher than those of PC2 (posterior areas) in EEG stages 8 and 9. Regarding the EEG stage variations, the results of post hoc testing revealed two groups among EEG stages [i.e. (stages 1 ~ 7) < (stages 8 and 9)] for PC2 (posterior areas). For PC1 (the anterior areas), post hoc testing revealed

four groups among EEG stages [i.e. (stages 1 ~ 6) < (stage 7) < (stage 8) < (stage 9)]. Inspection of the EEG records showed that the increase in scores of PC1 was related to the activity of the 14-Hz sleep spindle.

DISCUSSION

Topographical characteristics and PC structure

In the present study, we examined the topographical characteristics for nine EEG stages during the hypnagogic state. Topographic maps demonstrated that the dominant areas of alpha-band activity moved from the posterior areas to the anterior areas along the midline of the scalp. On the other hand, the dominant areas of delta-, theta-, and sigma-band activities did not move, but their activities developed in their focus areas of the scalp during the hypnagogic period. In the three latter frequency bands, the differences in EEG activities between the focus and surrounding areas increased as a function of EEG stage. These visual analyses were also supported by statistical examination; thus the need for statistical examination was suggested (27). To identify the dominant topographic components for each of six EEG band activities, PCA was carried out on the correlation matrix among 12-channel EEG data sets for each frequency band.

Slow-wave activities

Summarizing the topographic characteristics of slow-wave activity (delta- and theta-band activities) in the hypnagogic state, the nine EEG stages could be classified into three stage groups [i.e. (stages 1 ~ 5; from alpha-wave train to theta-wave burst suppression), (stage 6; vertex sharp wave solitary), and (stages 7 ~ 9; from vertex sharp-wave train or bursts to spindles)]. These suggest that background delta- and theta-band activities begin to increase amplitude and to extend their distributions on the scalp rapidly from the vertex sharp-wave state (stage 6).

Alpha-band activities

Alpha 1-band activity showed a single component structure of PCA and high factor loading in all regions. Alpha 1-band activity could be explained as the size factor that reflects the general increase of amplitude all over the scalp. However, the behavior of PC scores among EEG stages differed from that of theta-band activity. The PC scores showed a reversed J-shape curve with high values in EEG stages 1 and 2, then the scores decreased until EEG stage 5, while the scores recovered to the level of EEG stage 3 in EEG stage 9. It demonstrated that the topographic characteristics divided nine EEG stages into two stage groups [i.e. (stages 1 and 2; high-amplitude group), (stages 3 ~ 9; low-amplitude group)], and these two EEG stage groups correspond to stage W and sleep stages 1 and 2 in standard criteria, respectively (4).

Alpha 2-band activity was divided into two regional subgroups. One is on the anterior area from the frontal

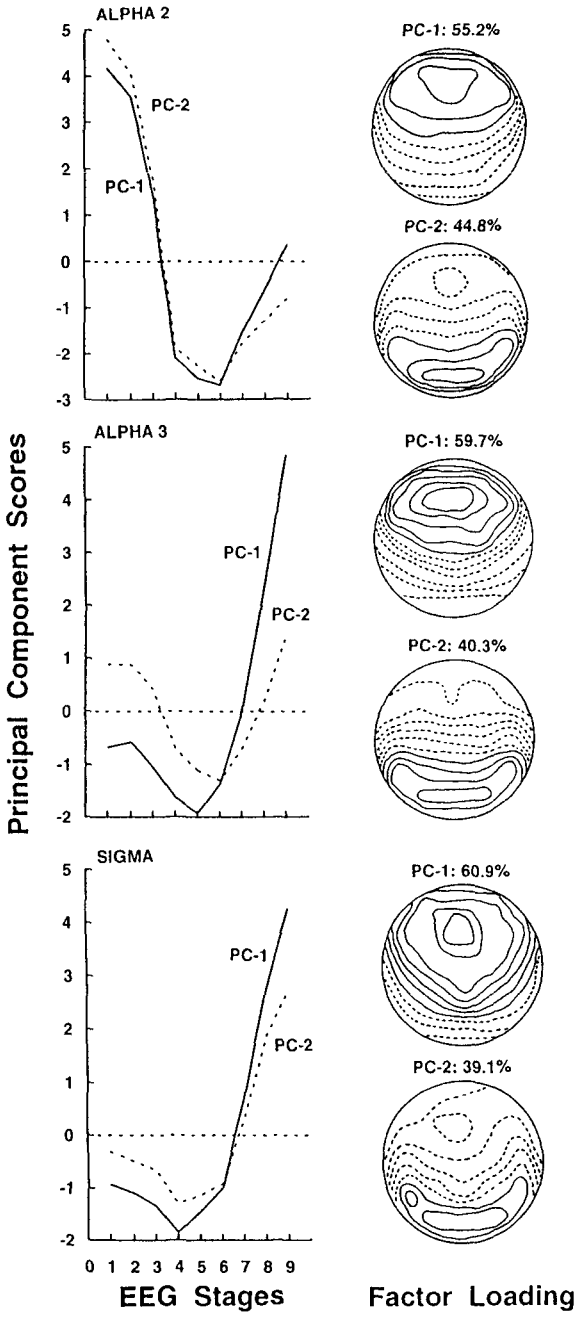

FIG. 4. Variations in averaged component scores for each electroencephalogram (EEG) stage (left three panels). Comparisons of topographic maps for factor-loading patterns for alpha 2, alpha 3, and sigma bands are provided in the three panels to the right. The solid line showing the >0.7 level of factor loading in the topographic maps shows the subgroups extracted by principal component analysis (PCA) to be the dominant topographic component.

pole to the central and the other is on the posterior area from the parietal to the occipital. These two components showed high PC scores during the waking state. Moreover, both components discriminated the alpha-dominant state (EEG stages 1 and 2, alpha ≥50%) from the alpha-intermittent state (alpha <50%). These findings suggest that the hypnagogic EEG changes occurred even within the period of EEG alpha prominence.

Ogilvie and colleagues (1–3) reported that lengthening response time and intermittent response failure started in drowsy wakefulness and standard sleep stage 1 and they suggested that the behavioral sleep process might start in the period of sleep stage 1. They (10) also reported that the N1 component of ERP, which relates mainly to level of attention, and ERP P300 amplitudes decreased significantly before behavioral sleep onset. Harsh et al. (11) reported that the latency of P300 increased during stage 1A (alpha present during 50–80% of the epoch), and the amplitude was substantially smaller in stage 1B (standard sleep stage 1). Additionally, Wesensten and Badia (28) reported a diminished and long latency P300 component relating to a decrease in waking level and indicated that significant change occurred before the disappearance of alpha waves. In the present study, the distribution of alpha 2-band activity on the scalp was clearly changed between before and just after EEG stage 3 (alpha intermittent, <50%), suggesting that the changing point of EEG topography may coincide with the changing point of behavioral and ERP components.

Principal component scores of PC1 (anterior component) for alpha 3-band activity showed a J-shaped curve in terms of EEG stages and started to increase from EEG stage 6. On the other hand, the activity of PC2 (posterior component) showed a reverse J-shaped curve that was dominant during waking, and the increment of the PC score after EEG stage 7 was not as clear as that of PC1 activity.

Ogilvie et al. (10) examined the ERP and EEG changes during sleep onset by behaviorally based differentiation (from bin 1 to bin 5). Bins 1 through 4 represented the shortest to longest response quartiles, respectively, and bin 5 contained EEG obtained during failed responses (behavioral sleep). They reported that both negative components N2 and N3 and positive components P1 and P3 of ERP increased significantly at behavioral sleep onset (bin 5), which indicated that these components would be good parameters to detect behavioral sleep onset. Additionally, they examined central EEG amplitude as well as ERP, which indicated that relatively high alpha levels typical of relaxed wakefulness (bin 1) give way to reduced alpha levels immediately prior to behavioral sleep (bin 2–4); however, alpha increases were again evident at sleep onset (bin 5). The changes were accompanied by significant alternations in the nature of the middle latency and long latency ERP components, namely, a sharp increase in P1, N2, N3, and P3 amplitude. In the present study, as the scalp distribution of alpha 3 activity became dominant in the anterior areas relative to the posterior areas after EEG stage 7 (vertex sharp-wave train or bursts), the amplitude increased and extended their distributions. Subsequently, the scalp distribution of alpha 3 activity was clearly changed after EEG stage 8 (vertex sharp-wave state), suggesting that the changing point (EEG stage 7 or 8) corresponds to the alternations of ERP components as well as behavioral sleep onset. These findings support Broughton's suggestion (9) that the appearance of vertex sharp wave is related with behavioral sleep onset.

On the other hand, concerning interregional relationships, the dominant areas of both alpha 2- and alpha 3-band activities moved from the posterior to the anterior areas during the process of sleep onset. The posterior components of these two alpha bands were more dominant than those of the anterior components in EEG stages 1 and 2. On the contrary, the anterior components were more dominant than those of the posterior components in EEG stages 8 and 9. Ozaki and Suzuki (29) reported the existence of two alpha-band activities: one is widespread alpha activity with maximal power in the parieto-occipital chain over both lateral areas and the other is local alpha in the anterior regions. As mentioned above, both of the alpha 2-band components (PC1, PC2) showed high scores during waking, suggesting that these band activities could reflect fluctuations of arousal levels. On the other hand, PC2 (posterior component) of alpha 3-band activity was dominant during waking, while the activity of PC1 (anterior component) became dominant from EEG stage 7. It was confirmed by visual inspection of the EEG record that the activity of the anterior component reflected the 12-Hz slow spindle activity. These findings suggest that the posterior components of the alpha 2 band reflect the waking alpha activity, while the anterior components of the alpha 3 band reflect the development of the 12-Hz slow spindle activity. The posterior components of the alpha 2 band started to decrease before the onset of sleep stage 1 in standard criteria (4). This shows that the structure of alpha band 2 activities changes between the full awake and sleep stages. Sleep onset process probably started before the onset of sleep stage 1 (4). On the other hand, the anterior components of the alpha 3 band started to increase before the onset of sleep stage 2 in standard criteria (4). These results suggest that the basic sleep process may start before the onset of the manually scored spindles or sleep stage 2 (4).

Sigma-band activities

Sigma-band activity was divided into two regional subgroups. One component had moderate or higher amplitude and was distributed across extensive scalp areas from the frontal to the parietal areas, and the other component had low amplitude and was restricted to the temporal-occipital areas. The first component increased sharply after the vertex sharp-wave train or bursts state (EEG stage 7) in which the clear scalp distribution pattern of sigma activity appeared on the EEG topographic map. The amplitude of the dominant component (PC1) was higher than the posterior component (PC2) in EEG stages 8 and 9. It was confirmed by visual inspection of EEG records that the dominant component (PC1) reflected the activity of the 14-Hz sleep spindle. Gibbs and Gibbs (20) described the two types of spindles, and indicated that the 14-Hz spindles were dominant in the parietal region, while the 12-Hz spindles were dominant in the frontal region. The examination of topography and coherence analysis (5,30) demonstrated the existence of these two different types of spindles. Our previous study (5), using topographic maps from consecutive samples of 20-second periods, demonstrated that the dominant region of the spindles mixture pattern was in the parietal area (in the sigma band; 13.0–14.5 Hz map) and in the frontal area it was the alpha 2 band (10.0–12.5 Hz). The appearances of these spindle mixture patterns were 2–3 minutes in advance of the manually scored spindles (i.e. having a duration of 0.5 second or more). On the other hand, Scheuler et al. (30) used consecutive 4-second epochs, averaging every 10 epochs (0.25 Hz resolution, reference; ipsilateral Cb electrodes). They reported that two different activities in the sleep spindle frequency band (11.00–12.75 Hz, 13.00–14.75 Hz) were discriminated regarding their frequency (12/14 Hz), spectral power distribution (premotor region/sensory region), and inter- as well as intrahemispheric coherence. Sleep researchers have found it convenient to divide EEG recordings into epochs of different durations (10, 20, or 30 seconds). In the present study, a 30- (5 minutes × 6 times) second epoch was used because this epoch length was most commonly used for sleep stage scoring. Another reason for this choice was to find a reasonable compromise between stability of spectral EEG data and the frequency resolution. In the present study, slow 12-Hz spindle activity was integrated in the alpha 3-band activity, and the 14-Hz spindle activity was integrated in sigma-band activity. The results of the present study support the traditional findings regarding two-spindle components and their scalp distributions. These neurophysiological findings suggest that these two activities within the sleep spindle frequency band are related to two functionally separate systems that differ not only topographically (one predominating in the premotor region, the other one in the sensory area) but also with regard to their temporal behavior composing the sleep onset process. If the spindle activity is an effective maker of the sleep process, these findings suggest that sleep onset processes are not uniform over all of the scalp EEG areas, and the basic sleep process may start in advance of the onset of the manually scored spindles. In the present study, sigma-band activity was differentiated into two components that corresponded with the activities on the central–parietal areas (high amplitude) and their surrounding areas (low amplitude), being extracted as the parameters to describe the development of sigma-band activity in the previous studies (31,32). Since scalp EEGs are thought to be influenced by the apparent relationships between channels, the structure of the principal component may be influenced by these interactions. Therefore, in the near future, it would be necessary to examine the coherence analyses of hypnagogic EEG, which are a measure of the linear correlation between two EEG derivations.

Additionally, the influence of the use of the ipsilateral earlobe reference upon topographic variations in EEG activity should be considered, since amplitude of the EEG varies as a function of interelectrode distance (i.e. the closer the electrodes, the smaller the potential difference). It is also important to consider the distance between the active EEG electrode and reference electrode sites. The activation of a reference electrode site is also a troublesome factor. This is especially so for slow activity, which tends to have broad fields. A reference electrode should be situated distant from many different sources. Although there is no perfect solution for these various reference electrode position-related problems, recognition of the situation is important (33). In many conventional EEG studies, a contralateral or occasionally ipsilateral earlobe or mastoid reference is employed. Another reference used especially in quantitative EEG studies involves linking electrodes placed on the earlobes. However, equalizing ear-reference impedance is not easily done, and the effect of unequal impedances in a linked-reference configuration would be to artifically inflate the amplitude of the leads on the side of the reference electrode of highest resistance. In the present study, the dominant area of each band activity agreed with the findings using ear-linked references (21,34). The above findings may suggest that the contribution from the reference signal appears to require less consideration in understanding the topographical variations found in this study.

The necessity of quantifing scalp distributions of the dominant EEG component in the sleep onset period

In the present study, the dominant areas of alpha 2- and alpha 3-band activities moved from the poste-

rior areas to the anterior areas along the midline of the scalp during the waking–sleeping transition period. These findings suggest that the changes of the scalp distribution of the dominant EEG activity reflect the state changes accompanied with the approach of sleep onset. These changes of EEG amplitude coincided with the regional changes of ERP components as reported in other studies. The study of the relationship between ERP and behavioral changes during the waking and sleeping transition indicates that a parietal P300 disappears in association with reduced behavioral responsiveness (10,11) and the emergence of a central N350 (11). Harsh et al. (11) also reported that N350 occurred early in sleep onset (sleep stage 1) and with a maximum amplitude at the vertex, whereas N550 was more evident on the frontal region later in sleep onset (sleep stage 2). Ujszászi and Halász (35,36) speculated that the two components were the result of parallel processes, with the initial component (N350) connected more closely with information processing and the second component (N550) related to sleep state-dependent processes. Summarizing the results of ERP studies, the scalp distribution of the dominant ERP components moved from the posterior to the anterior areas, accompanied with the approach of sleep onset. It may be concluded, from what has been stated above, that the movements of the dominant areas of background EEG activities from the posterior areas to the anterior areas reflect that brain activities become anterior dominant in the late sleep onset period, which includes the information processing mechanism. These findings suggest that the sleep onset processes start in the anterior areas, including the premotor cortex, and spread all over the scalp (i.e sensory cortex). The decreasing of the function of the premotor cortex, which precedes the decreasing of the function of other sensory cortices, may be related to the process of behavioral sleep onset. Additionally, these findings suggest that the characteristics of hypnagogic EEG could not be described by a single EEG derivation; two or more anterior–posterior EEG derivations were needed to understand the phenomena.

Jobert et al. (37) investigated both the EEG activity and the underlying sleep process by using PCA of all-night spectral EEG. Independent of the electrode locations, the factor loading (FL) pattern of PC1 showed a high correlation with all frequency ranges (0.5–30.0 Hz) except for the 4.0–8.0-Hz frequency ranges. Conversely, the FL pattern of PC2 correlated with delta 2- (2.0–4.0 Hz) and theta- (4.0–8.0 Hz) frequency ranges. While there was considerable agreement between the PC scores of PC1 and the conventional hypnogram, the most clear-cut differences between the two parameters were the slow and continuous variations of PC scores of PC1 in contrast to the extended episodes of the same sleep stage with abrupt transitions between stages as displayed by hypnograms. They commented that the PCA of EEG activity reinforced the conceptualization of gradual time-dependent variations in the sleep process [i.e. synchronization and desynchronization of EEG activities within a rapid–nonrapid eye movement (REM/NREM) cycle]. Additionally, their data suggest that the PC scores of PC1 (broad-band integration) are sensitive to evaluate the sleep onset latency. However, the spatial information gained by combining results recorded from distinct brain regions is not a distinctive feature of the PCA. To integrate these findings with our results, the alpha- and sigma-band activities are sensitive enough to investigate the process of sleep onset rather than the conventional slow-wave activities. These suggest that the movements of the dominant areas of EEG activity, from the posterior areas to the anterior ones, may become key variables in describing the process of sleep onset.

Recently, Hori et al. (18) reported that the anterior–posterior EEG ratio (A/P ratio) of alpha-band activity increased from stage 1 to stage 9 as a function of the EEG stages of the hypnagogic state and that the A/P ratio clearly changed between the alpha intermittent state (EEG stage 3) and EEG flattening state (EEG stage 4). These results suggest that this ratio is sensitive enough to detect the start of a sleep onset period and could be used as an objective indicator to gauge the approach of true sleep onset without interrupting the natural hypnagogic process. To find a cue for the all-inclusive study of the hypnagogic state, it is necessary to assess the point of convergence of behavioral (reaction time, RT) (17) and subjective (hypnagogic imagery, HI) (18) measures on the nine EEG stages of the hypnagogic period.

The present study identified the dominant topographic components and examined the regional differences of EEG activity by PCA. The results of PCA revealed that the two dominant components existed in alpha 2-, alpha 3-, and sigma-band activities, although the A/P ratio has never been reported [as mentioned above (18)] in which all alpha activities were combined into a single alpha-band activity. Further research is needed to examine the A/P ratios of both alpha 2- and alpha 3-band activities. It is expected that these two A/P ratios would be sensitive indicators to discriminate the variable states of the sleep onset period. Moreover, if we enlarge the idea of the ratio of the regional differences, the focus–surround ratio of sigma-band activity may be expected to show a stage profile different from that of the A/P ratio of alpha-band activity.

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