Awareness during drowsiness: Dynamics and electrophysiological correlates

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Abstract

Examined performance patterns and concurrent EEG spectra in 4 Ss (mean age of 30.5 yrs) performing a continuous visuomotor compensatory tracking task in 15–20 min bouts during a 42-hr sleep deprivation study. During periods of good performance, participants made compensatory trackball movements about twice per second, attempting to keep a target disk near a central ring. Results indicate that autocorrelations of time series representing the distance of the target disk from the ring center showed that during periods of poor performance marked near-18-sec cycles in performance again appeared. There were phases of poor or absent performance accompanied by an increase in EEG power that was largest at 3–4 Hz. These studies show that in drowsy humans, opening and closing of the gates of behavioral awareness is marked not by the appearance of (12–14 Hz) sleep spindles, but by prominent EEG amplitude changes in the low theta band. Further, both EEG and behavioral changes during drowsiness often exhibit stereotyped 18-sec cycles.

Methods

Participants. Four young adults (mean age = 30.5, SD = 5.0 years) volunteered to participate in this experiment. None reported a history of neurological or psychiatric disorder.

EEG Recording. The EEG was recorded from electrodes placed at left frontal (F3), right central (C4), right parietal (P4), and left occipital (O1) sites. The reference was the left mastoid (M1). Eye movements and blinks were monitored via two electrooculogram (EOG) channels. The EEG and EOG activity were digitized at a sampling rate of 125 Hz. EEG spectra were extracted by Hanning-windowed Fast Fourier analysis performed on overlapping 2-s epochs from the continuous EEG data record. Epochs contaminated by EOG and muscle artifact were rejected. Data from the right-central EEG channel (C4) are reported here.

Procedure. Participants arrived in the laboratory in the morning (10:00). They were then sleep deprived for 42 hours. During the 42-hour sleep deprivation period, participants performed 9–10 bouts of two tasks at roughly 4-hour intervals: a psychomotor vigilance task, designed by <u>Dinges</u> and Powell (1985) lasting 20 minutes, followed after a 1–2 minute break by a continuous visuospatial compensatory tracking task (CTT) lasting 20 minutes. (At one participant's request, tracking bouts were limited to 15 minutes.) Staff technicians were instructed not to alert participants who stopped responding during either task. In the present study, data from the tracking task are reported.

In the tracking task, participants manipulate a trackball to counter unseen quasi-random forces tending to "blow" a circular disk off an invisible slippery slope around the screen centre marked by a visible ring. Participants attempt to use rapid, small trackball movements to maintain the disk near the centre of the ring. At each program step (about 14 times per second), the disk is moved according to the vectorial sum of forces acting on it — the unseen "wind" plus the simulated "force of gravity" plus a directed force proportional to the most recent trackball velocity. The tracking performance measure we employed was the average distance of the moving disk from the fixed central ring. (For more details and program code, see <u>Makeig & Jolley, 1996</u>).

In constructing the moving-mean performance measure, the disk-distance time series was first rescaled from units of screen pixels to disk diameters, and then passed through a sigmoidal *erf* function whose lower asymptote was tied to the participant's best performance in the indicated baseline bout. Here, best performance was quantified as the 10th percentile in the participant's histogram of mean disk-distance smoothed using a 2-min window moved through the data in 2-s steps. In previous studies, changes in mean tracking disk distance have been associated with fatigue (Makeig & Jolley, 1996) and with concurrent changes in eye activity and performance consistent with drowsiness (Van Orden, Jung, & Makeig, 2000).

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The disk distance measure was then linearly rescaled to [0,1] with the upper bound scaled to place its upper asymptote at the measured mean disk distance in the absence of any participant input (9.4 disk radii). The disk distance time series were then smoothed using a 90-s square window moved through the data in 1-s steps, producing an individual *mean error* measure that varied smoothly between 0 (best participant performance) and 1 (no effective participant input).

To look for periodicities in participant performance, the raw target-distance time series for each overlapping 90-s epoch used in computing the smoothed distance measure was autocorrelated, and the resulting autocorrelation time series were sorted on mean disk distance in the same epochs. Autocorrelation refers to variably lagged correlations of a time series with itself. Here, for convenience, unscaled autocorrelations were computed using the MATLAB function, *xcorr* (The MathWorks, Natick MA). Finally, the autocorrelation time series were converted to power spectra by FFT analysis.

Results



Figure 1. Grand mean performance autocorrelation (self-correlation of the raw disk-distance time series as a function of temporal lag (x-axis) and mean normalized disk distance (y-axis). Small normalized disk distances (0.30) indicate periods of relatively continuous good performance, while large distances (0.80) indicate periods of largely ineffective and/or absent performance. Data averaged over all four participants. Grey scale: lagged autocorrelation of the performance time series (relative units). Note the 15-20 s performance cycles during periods of relatively large disk distance (e.g., between 0.60 and 0.70), as indicated by the flanking light and dark spots near 10 s and 20 s lags respectively.

Figure 1 illustrates the mean performance autocorrelation time series sorted by smoothed disk distance and averaged across the four participants. An indication of a near 20-s performance cycle appeared at disk distances between 0.60 and 0.70 as a cycling between negative (light) and positive (dark) values at near 9-s intervals on either side of the central zero lag.

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Figure 2. Grand mean power spectra (all 4 participants) of the performance time series autocorrelations (Fig. 1) sorted by performance error (normalized disk distance). X-axis: cycle frequency (Hz). Y-axis: Normalized disk distance. Gray scale: Mean cycle amplitude (change in disk distance per second). At relatively poor mean performance levels (0.5 to 0.7), a peak in the performance autocorrelation spectrum appears near 0.05 Hz, indicating the appearance of circa 20 s cycles between good (alert) and poor (or absent) performance (cf. Fig. 4 for example).

Spectra of these same autocorrelation time series are

illustrated in Figure 2, again sorted by disk distance. The near 18-s cycle length was confirmed by this analysis at normalized disk distances between 0.50 and 0.70. This 18-s cycling was expressed exactly in the autocorrelation spectra of two of the participants, whereas for the other two participants the implied periodicity was weaker and somewhat longer.



Figure 3. Autocorrelations of disk distance time series for one participant sorted by normalized disk distance. Gray scale: unnormalized autocorrelation in relative units (here dark is positive). At disk distances near 0.70, a marked circa 18-s lag correlation appears.

Figure 3 (above) shows the sorted autocorrelations of the performance time series for one participant, averaged over eight task bouts, showing the 18-s

cycle at disk distances near 0.70. A marked example of near 18-s cycling behaviour from this participant is shown in **Figure 4** (below). The left panel plots the distance of the disk from the target ring during the first two minutes of a task bout performed after 32 hours of sleep deprivation. Periods of good performance (i.e., low disk distance, for example near 80 s) alternate with periods in which the target escaped to levels near 1.0 compatible with complete lack of participant input. The autocorrelation of this performance time series (right panel) demonstrates the dominant 18-s periodicity.



Figure 4. (left panel) Time course of performance fluctuations (actual disk distances in disk radii) at the beginning of a bout recorded after 32 hr of sleep deprivation (same participant as Fig. 3), exhibiting marked circa 18 s performance cycles. (right panel) An unnormalized autocorrelation of the same performance time series shows positive (correlation) peaks at time lags near 18 s, confirming the predominant 18 s performance periodicity in the record.

Figure 5 (below) shows the grand mean EEG spectra for all four participants at right central electrode site C4, constructed by first sorting the spectra for each of the 13,000 3-s trials by disk distance and then smoothing the resulting image with a 0.05-wide smoothing window. The prevailing disk distance is shown in the figure by a thick black line whose x-value is 10 times the prevailing disk distance (e.g., the thick line x-value of 7 represents disk distance = 0.70). The figure shows that the general increase in low-frequency EEG power during poor performance (i.e., at relatively large disk distances) was largest near 3 Hz. The approximately 3-Hz peak was present in data from all four participants. However, no specific increase at sleep spindling frequencies (12–14 Hz) is visible even at maximum disk distance.



Figure 5. EEG spectra at right central site C4 in 13,000 2 s task data windows (from all 4 29 participants) sorted by normalized disk distance in the 90 s window centered on the 2 28 s data window. X-axis: EEG frequency (Hz). 27 Y-axis: sorted trial number. Gray scale: relative log EEG spectral power. The x-values 26 of points on the diagonal black trace indicate the normalized disk distance (times 10). Note 25 the increase in EEG power between 2-5 Hz power during periods of relatively poor 24 performance (e.g., normalized disk distances above 0.5). 23

Discussion

These results for a visuospatial task performed during sleep deprivation replicate our previous findings using an auditory detection task. In the previous study, participants had not been specifically sleep deprived. Participants simply had to monitor a noise stream for brief amplitude shifts and respond to each shift with a button press. In the compensatory tracking task reported here, participants had to continuously observe and attempt to compensate for small changes in the rate and direction of continuous movement of a target disk. During good performance, participants in this task make about two corrective calibrated hand and finger movements per second, whereas only about 10 button presses per minute were required in the auditory task. The similarity of the changes in performance and EEG dynamics observed in the two different tasks suggest they may be common to drowsy performance in any sustained sensorimotor task. For both tasks, the most prominent change in the EEG spectrum correlated with performance degradation is an increase in power in the 2–5 Hz low theta range. This increase was found whether the data were averaged over seconds or minutes. For both tasks, 18-s periodicities in performance and low theta EEG were observed during periods of intermittent performance during drowsiness.

Cross-correlation analysis on EEG spectra and performance time series were carried out for a single participant using consecutive 2-s windows. The resulting cross-correlation time series was then sorted by mean performance computed in a 90-s window centred on each epoch. Results confirmed the relation of 2–5 Hz log theta EEG power to 18-s performance cycles at high disk distances (<u>Figure 5</u>). The correlation between performance and gamma band EEG power was however very small. Possibly such a correlation may have been masked by EEG variability introduced by the constant random movements of the target disk, the difficulty of the task, and/or the required frequent and rapid finger movements.

Notably, the approximately 18-s performance cycling seen in 7 of 10 participants for the auditory detection task (Makeig & Jung, 1996) again occurred for at least two of the four participants in the compensatory tracking task. Thus, as was first reported from visual inspection of EEG tracings during sleep deprivation (Williams et al., 1962), the opening and closing of the gate of awareness and task performance capacity during drowsiness tends to occur in characteristic 18-s cycles, and is accompanied or indexed by amplitude changes in EEG activity in the 2–5 Hz low theta range rather than by the appearance of sleep spindles. Colrain, Di Parsa, and Gora (this issue) also report that marked changes in both auditory- and respiratory-evoked potentials occur when the EEG is dominated by theta activity during Stage 1 sleep. It would be interesting to learn whether the 18-s cycles also appear as EEG fluctuations in participants who attempt to go to sleep, rather than in participants who (as here) attempt to stay awake.

The 18-s cycling behaviour is reminiscent of the alternating brief periods of relative alertness and drowsiness often seen in other mammals. Rajkowski and colleagues have

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presented evidence that changes in noradrenergic activation in the locus coeruleus precedes both the EEG spectral and accompanying behavioural vigilance shifts in monkeys (<u>Rajkowski</u>, <u>Kubiak</u>, <u>& Aston-Jones</u>, 1994). The locus coeruleus is one of a number of subcortical loci involved in modulating cortical activity and awareness. It is quite possible that their effects on cortical processing might be indexed by spectral shifts in the scalp EEG such as those reported here. In the present study, spectral estimation was applied to recordings from a single scalp electrode. Studies of these or similar data recorded at larger numbers of EEG electrodes using independent component analysis (<u>Makeig et al., 1996, 1999</u>) might also reveal more information about the spatial sources of the EEG changes and their dynamics. Elsewhere, we have shown that the relationship between EEG spectral changes and performance impairments in drowsiness is sufficiently robust that individualized EEG models can accurately estimate performance in near real-time from EEG data (Jung, Makeig, Stensmo, & Sejnowski, 1997; Makeig & Inlow, 1993).

The results presented here reinforce four conclusions about dynamics of human awareness, concomitant performance changes, and EEG spectral power changes during drowsiness: (1) During periods of marked drowsiness, stereotyped cycles alternating between wake-like and sleep-like performance and in EEGpower often occur; (2) During these cycles, phases of poor or absent performance are paralleled by increases in low-frequency (circa 4-Hz) theta activity; (3) Often, these cycles have periods near 18 seconds; (4) These performance and EEG cycles occur in the absence of any specific increase in EEG power at the 12–14 Hz human sleep spindle frequencies.

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