PAPER

Oscillatory Neural Activity during Performance of a Cognitive Task in the Presence of Fluctuating Ambient Noise*

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SUMMARY The purpose of this study was to identify the key variables that determine the quality of the auditory environment, for the purposes of workplace auditory design and assessment. To this end, we characterized changes in oscillatory neural activity in electroencephalographic (EEG) data recorded from subjects who performed an intellectual activity while exposed to fluctuating ambient noise. Seven healthy men participated in the study. Subjects performed a verbal and spatial task that used the 3-back task paradigm to study working memory. During the task, subjects were presented with auditory stimuli grouped by increasing high-frequency content: (1) a sound with frequencies similar to Brownian noise and no modulation; (2) an amplitude-modulated sound with frequencies similar to white noise; (3) amplitude-modulated pink noise; and (4) amplitude-modulated Brownian noise. Upon presentation, we observed a characteristic change in three EEG bands: theta (4–8 Hz), alpha (8–13 Hz), and beta (13–30 Hz). In particular, a frequency-dependent enhancement and reduction of power was observed in the theta and beta bands, respectively.

key words: workplace auditory evaluation, fluctuating ambient noise, oscillatory neural activity, 3-back task

1. Introduction

The quality of our auditory environment is closely related to our quality of life, and has the potential to improve the performance of intellectual activities and productivity if appropriately regulated.

It is difficult for users to control the auditory environment by themselves, although they can usually control the visual environment relatively easily by simply closing their eyes. Therefore, a need exists for some equipment or design optimization to control the auditory environment based on scientific verities.

In previous work, we characterized the neural activation associated with the performance of intellectual activities under the influence of ambient noise [1], by introducing a fluctuating ambient sound [2] made by modulating the amplitude of Brownian noise, which was suggested to be analogous to the environmental noises found in real

workplaces [3]. In the study, an ERP (event-related potential) in the brain was measured and analyzed, to evaluate how the fluctuating noises affected cognitive processes in terms of a 3-back task. Working memory studies have also used the *N*-back task, which is a test of working memory function during imposition of a continuous, parametrically variable load [4]. The results suggested that in a spatial 3-back task, ambient noise with the frequency characteristics of white noise affects the attentional function associated with working memory. However, no differences in reaction time were found across different fluctuating noises. In the present study, instead of ERPs, we focused on the oscillatory neural activities seen in the electroencephalogram (EEG), grouped in ascending frequency bands as theta, alpha, and beta rhythms, to study the functioning of cognitive process such as working memory, attention, and visual awareness [5]–[10]. This paradigm could be expected to reveal novel associations between the auditory environment and cognitive function.

Therefore, as a follow-up to our previous ERP study [3], the present study aimed to evaluate how fluctuating ambient noises affect the neural activities related to cognitive processing by analyzing EEG rhythms in order to identify the neurophysiological markers that could guide the design of optimal auditory environments.

2. Methods

2.1 Ambient Noises

The following four types of ambient noise were used in this study: (1) a low-pass sound with 6 dB/oct between 0.1 and 8 kHz, similar to Brownian noise, without amplitude modulation; (2) a sound modulating the amplitude of sound (1) with white noise, such that the slope of the power spectral density equals zero ($1/f^0$: *White*) between 0.05 and 1 Hz; (3) a sound modulating it with pink noise, ($1/f^1$: *Pink*); and (4) a sound modulating it with Brownian noise ($1/f^2$: *Brownian*) as well as sound (2). These ambient noises decrease the high frequency component in the order of *White*, *Pink*, and *Brownian*. The Brownian noise of (1) was just a carrier signal without modulation (*NM*: No Modulation). These ambient noises were presented with an equivalent sound pressure level of 50 dB(A).

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2.2 Tasks

Seven healthy men aged 21–23 years with normal vision participated in the experiment. All participants provided written, informed consent, and the study design was approved by the ethics committee of the Division of Human Informatics of the Graduate School of Tohoku Gakuin University. Subjects executed a working memory task, the N -back task, during exposure to ambient noises. As shown in Fig. 1, the paradigm comprised verbal and spatial tasks. In the verbal task, alphabetic characters were presented sequentially and subjects were required to state whether the character currently presented matched the one presented 3 items earlier (i.e., presented 3-back of the current one) in the series. In the spatial task, subjects were asked to identify the position of the character on the screen. The verbal task was assumed to capture the characteristics of intellectual workplace activities such as creating a document containing embedded numbers, words, and sentences. The spatial task was assumed to do the same for activities such as drawing a plan showing the spatial configuration of items. The accuracy rates and reaction times (RTs) in both tasks were measured from computer mouse button-press events: in the case of a match, the subjects clicked the left mouse button, and in the case of a non-match, the right mouse button. In both tasks, a series of 53 characters was presented. Each character had a luminance of 3 cd/m², measured 1.3° × 1.3°, and was placed on a black background on a CRT screen (Trinitron Multi-scan E200, SONY) in one of twelve positions located 1.9°

Fig. 1 In both tasks, a series of 53 characters was presented. Each character was placed in 1 of 12 positions, which were located 1.9° or 5.7° away from the cue symbol (+) at an angle of 0°, 60°, 120°, 180°, 240° or 300° on a black CRT screen. Each was presented for 250 ms, and the interval between the presentations of 2 successive characters was 4.5 s. Reaction times were measured by means of a computer; in the case of a match, the subjects clicked the left mouse button, and in the case of a non-match, the right mouse button.

or 5.7° away from the cue symbol (+) at an angle of 0°, 60°, 120°, 180°, 240°, or 300°. Each character was presented for 250 ms, and the interval between two successive presentations was 4.5 s.

2.3 Data Analysis

The present study uses the EEG dataset collected in our previous study [3]. Briefly, EEG data were recorded from 60 channels/scalp locations (F_{p1} , F_{p2} , AF_7 , AF_3 , AF_z , AF_4 , AF_8 , F_7 , F_5 , F_3 , F_1 , F_z , F_2 , F_4 , F_6 , F_8 , FT_7 , FC_5 , FC_3 , FC_1 , FC_z , FC_2 , FC_4 , FC_6 , FT_8 , T_7 , C_5 , C_3 , C_1 , C_z , C_2 , C_4 , C_6 , T_8 , TP_7 , CP_5 , CP_3 , CP_1 , CP_z , CP_2 , CP_4 , CP_6 , TP_8 , P_7 , P_5 , P_3 , P_1 , P_z , P_2 , P_4 , P_6 , P_8 , PO_7 , PO_3 , PO_z , PO_4 , PO_8 , O_1 , O_z , O_2) referenced to linked ears. Sampling was at 500 Hz and we used the Neurofax EEG-110 amplifier (Nihon Koden Corporation).

Data epochs were extracted for the period spanning 2,000 ms pre-stimulus to 2,000 ms post-stimulus, with reference to a trigger signal presented at character onset, and were grouped for analysis by each of eight conditions: 2 tasks × 4 types of ambient noise.

For analysis and comparison of event-related synchronization (ERS) and event-related desynchronization (ERD) [11], a continuous wavelet transform was conducted for each EEG epoch from 1 to 80 Hz, changing the center frequency of the mother function by 1-Hz steps to obtain the time-frequency responses. The Morlet function was the mother wavelet. Epochs including artifacts exceeding 100 μV between 500 ms pre-stimulus and 1,000 ms post-stimulus were excluded. The intertrial variances of the wavelet coefficients were calculated for each frequency using the equation below (1) [10].

$$Variance(j) = \frac{1}{N-1} \sum_{i=1}^N \{x_{f(i,j)} - \bar{X}_{f(j)}\}^2, \quad (1)$$

where N = the total number of trials for each condition (50 maximum), $x_{f(i,j)}$ denotes the j -th sample (wavelet coefficients) of the i -th trial, and $\bar{X}_{f(j)}$ represents the mean data at the j -th sample. The value of the pre-stimulus period from 2,000 ms pre-stimulus to 0 ms served as the 100% value for baseline normalization.

The band-averaged variances in the theta (4–8 Hz), alpha (8–13 Hz), beta (13–30 Hz), and gamma bands (30–80 Hz) were then calculated, and the resulting time functions were smoothed with a low-pass digital filter with a 4 Hz cut-off frequency [10].

Repeated-measures analysis of variance (ANOVA) was performed on the band-averaged data for task (2 levels: Verbal/Spatial) and ambient noise (4 levels: *NM/White/Pink/Brownian*). In this statistical test, subject was a repeated factor and channels were measurement variables. Multiple comparisons were then performed for each band using Bonferroni's procedure based on paired t -tests.

See Ref. [3] for detailed descriptions of ambient noises, tasks, and EEG measurement procedures.

3. Results

3.1 Time-Frequency Fluctuation

Figure 2 shows the time-frequency characteristics found in the midline area (F_z , C_z , P_z , and O_z) for the normalized intertrial variances from 1 to 80 Hz for each task. The intertrial variances were averaged over all ambient noises and all subjects for each task to evaluate task differences in ERS (measured as variance decrease) and ERS (measured as variance increase). For each task, the ERS was measured from 4 to 13 Hz at latencies of 0 to 800 ms, and the ERD was measured from 8 to 30 Hz at latencies of 300 to 600 ms. However, we found little difference between tasks from these results. The only difference was a slightly larger ERS in the spatial task than the verbal task at latencies from 500 to 1,000 ms in the gamma band.

Fig. 2 Intertrial variances from 1 to 80 Hz at F_z , C_z , P_z , and O_z in the verbal task (left) and spatial task (right), averaged over all subjects and auditory stimuli. White and black colors indicate event-related synchronization (ERS) and desynchronization (ERD), respectively. Horizontal lines demarcate, from top to bottom, gamma, beta, alpha, theta, and delta bands.

3.2 Time Course for Each Frequency Band

Figure 3 shows the time courses of the band-averaged variances for the theta (4–8 Hz), alpha (8–13 Hz), and beta bands (13–30 Hz). The data was re-calculated for the theta and alpha bands with 0.05-Hz steps, for the beta band with 0.2-Hz steps, and for the gamma band with 0.5-Hz steps.

The electrode channel C_z in the theta and beta bands, and P_z in the alpha band, indicated characteristic fluctuations. An ERS peak was observed in the theta band at 300 ms in the verbal task and at 298 ms in the spatial task, as well as in the alpha band at 190 ms and 210 ms, respectively. In addition to the alpha-ERS, alpha-ERD peaks were also observed for the two tasks at 480 ms and 498 ms, respectively. In the beta band, ERD peaks for the two tasks were observed at 398 ms and 348 ms, respectively. Gamma band activity showed no significant differences among tasks or noises.

3.3 Statistical Results

Table 1 shows the ANOVA results for the band-averaged

Fig. 3 Time course of band-averaged variances for the verbal and spatial tasks averaged over all subjects and stimuli, at C_z for the theta band (upper panel), at P_z for the alpha band (middle panel), and at C_z for the beta band (lower panel). Solid and dotted lines indicate the verbal and spatial tasks, respectively. ERS, event-related synchronization; ERD, event-related desynchronization.

Table 1 Results of analyses of variance on event-related synchronization (ERS) and desynchronization (EDS).

Frequency	Comparison	Channel	F ratio, probability and η^2
Theta ERS	Task	FC_5	$F(1, 6) = 6.445, P < 0.05, 0.0844$
		C_5	$F(1, 6) = 6.705, P < 0.05, 0.128$
	Ambient Noise	-	-
	Task $\times$ Noise	AF_7	$F(1.84, 11.0) = 4.563, P < 0.05, 0.0600$ Correction of Greenhouse-Geisser ε
		AF_8	$F(3, 18) = 4.468, P < 0.05, 0.0744$
		F_7	$F(3, 18) = 3.681, P < 0.05, 0.0865$
		F_5	$F(3, 18) = 5.010, P < 0.05, 0.0969$
		F_3	$F(3, 18) = 3.499, P < 0.05, 0.0839$
		F_6	$F(3, 18) = 5.501, P < 0.01, 0.171$
		F_8	$F(3, 18) = 4.402, P < 0.05, 0.134$
		FT_7	$F(3, 18) = 3.349, P < 0.05, 0.119$
		FT_8	$F(3, 18) = 3.985, P < 0.05, 0.133$
Alpha ERS	Task	-	-
	Ambient Noise	-	-
	Task $\times$ Noise	-	-
Alpha ERD	Task	AF_7	$F(1, 6) = 6.627, P < 0.05, 0.108$
		F_5	$F(1, 6) = 6.034, P < 0.05, 0.0810$
		FC_2	$F(1, 6) = 7.726, P < 0.05, 0.0733$
		FC_4	$F(1, 6) = 6.417, P < 0.05, 0.0467$
	Ambient Noise	-	-
	Task $\times$ Noise	-	-
Beta ERD	Task	F_7	$F(1, 6) = 7.040, P < 0.05, 0.178$
		F_3	$F(1, 6) = 9.427, P < 0.05, 0.132$
		F_1	$F(1, 6) = 6.925, P < 0.05, 0.093$
		F_2	$F(1, 6) = 6.146, P < 0.05, 0.113$
		FC_5	$F(1, 6) = 11.506, P < 0.05, 0.148$
		FC_3	$F(1, 6) = 7.176, P < 0.05, 0.0932$
		C_3	$F(1, 6) = 7.168, P < 0.05, 0.159$
	Ambient Noise	-	-
	Task $\times$ Noise	F_7	$F(3, 18) = 4.180, P < 0.05, 0.0730$
		F_3	$F(3, 18) = 4.538, P < 0.05, 0.107$
		F_1	$F(3, 18) = 4.410, P < 0.05, 0.117$
		F_2	$F(3, 18) = 3.411, P < 0.05, 0.0884$
		C_2	$F(3, 18) = 4.077, P < 0.05, 0.122$

variances, which were themselves averaged over the duration of the ERS/ERD peaks. Data were time-averaged variances between peak latencies ± 124 ms. Figures 4, 6, 8, and 10 show the channel locations of significant differences among the noises for each task, and of significant differences between tasks for each noise, according to Bonferroni's procedure ($p < 0.05$, $d \geq 0.5$ corresponds to a medium-sized effect). Not included in the results presented here are cases where only one channel showed a significant difference.

3.3.1 θ -Band ERS

A significant difference in theta-ERS was observed between tasks in the left fronto-central area, at FC_5 and C_5 (Table 1).

θ ERS

Fig. 4 Electrode positions indicating the locations of significant differences in theta-band event-related synchronization (ERS; hatched circles) found in multiple-comparisons testing ($p < 0.05$).

As shown in Fig. 4, significant differences were observed in the right occipital area at PO_8 and O_2 when presenting *NM*; in FT_8 and in the left fronto-central area (F_7 , F_5 , F_3 , FT_7 , FC_5 , FC_3 , and C_5) when presenting *White*; in the right frontal area (AF_8 , F_6 , and F_8) and in the left parieto-centro-temporal area (T_7 and CP_5) when presenting *Pink*; and in the left frontal area (AF_7 , F_7 , and F_5) when presenting *Brownian*.

Figure 5 quantitatively shows the t -test statistics averaged over all channels, showing significant differences for the comparisons corresponding among others to Fig. 4. As demonstrated in Fig. 5, the difference in ERS activity between tasks for the specific noise was identified.

Figure 5 (a) provides t -test statistics averaged over PO_8 and O_2 , which indicate significant differences between tasks for *NM*. The results indicated a larger ERS in the spatial task than in the verbal task (less than zero corresponds Verbal < Spatial). Figure 5 (c-1) shows t -test statistics averaged over AF_8 , F_6 and F_8 , which indicated larger ERS in the verbal task than the spatial task (more than zero). On the contrary, as shown in Fig. 5 (c-2), differences averaged over T_7 and CP_5 indicated a larger ERS in the spatial task than in the verbal task (less than zero) for *Pink*. Figure 5 (b) indicates the significant larger ERS occurring for *White* in the spatial task. Figure 5 (d) indicates a significantly larger ERS occurred for the *Brownian* sound in the verbal task. In addition to these results, averaged t -test statistics for *White* exceeded the threshold of significant difference coincidentally with *Brownian*, indicating a significantly larger ERS in the spatial task. Note that the region in the left-frontal area in Fig. 4 (d) almost corresponds with that in Fig. 4 (b) for *White*.

The result indicates a progressively smaller decrease

Fig. 5 Mean t -test statistics $\pm$ S.E. averaged over channels showing significant differences in theta-band event-related synchronization (ERS) in Fig. 4. The horizontal line shows the level of significance for $p < 0.05$.

α ERS

Fig. 6 Electrode positions indicating the locations of significant differences in alpha-band event-related synchronization (ERS; hatched circles) found in multiple-comparisons testing ($p < 0.05$).

(a) Between *NM-White* in verbal task (*NM* > *White*)

(b) Between tasks for *NM* (Verbal > Spatial)

Fig. 7 Mean t -test statistics $\pm$ S.E. averaged over channels showing significant differences in alpha-band event-related synchronization (ERS) in Fig. 6. The horizontal line shows the level of significance for $p < 0.05$.

in the difference in the ERS, and progressed inversely with the increase in the high frequency component (i.e., smaller decreases from *Brownian* to *Pink* to *White*).

3.3.2 α -Band ERS

In the alpha-ERS, ANOVA showed no significant differences between tasks and noises. In Fig. 6, however, multiple-comparisons analysis of the noise type found significant differences between *NM-White* in the prefrontal area at F_{p2} and AF_4 in the verbal task (Fig. 6(a)). In Fig. 6(b), significant differences between tasks are seen in the prefrontal, frontal, and central areas at F_{p2} , AF_8 , FC_z , C_1 , and C_z when presenting *NM*.

Figure 7 shows quantitatively the t -test statistics averaged over the channels showing significant differences in Fig. 6. In Fig. 7(a), significantly greater alpha-ERS is ob-

Fig. 8 Electrode positions indicating the locations of significant differences in alpha-band event-related desynchronization (ERD; hatched circles) found in multiple-comparisons testing ($p < 0.05$).

Between tasks for *White* (Verbal < Spatial)

Fig. 9 Mean t -test statistics $\pm$ S.E. averaged over channels showing significant differences in alpha-band event-related desynchronization (ERD) in Fig. 8. The horizontal line shows the level of significance for $p < 0.05$.

served in *NM* compared with *White* in the verbal task (more than zero). Figure 7(b) indicates larger alpha-ERS in the verbal task than in the spatial task for *NM* (more than zero).

3.3.3 α -Band ERD

In the alpha-band ERD, the left frontal area at AF_7 and F_5 , and the right fronto-central area at FC_2 and FC_4 , indicated significant differences between tasks (see Table 1). Figure 8 indicates significant differences between tasks in the frontal area at AF_4 , F_5 , F_3 , F_1 , F_2 , F_4 , F_6 , F_8 , FT_7 , FC_5 , FC_2 , FC_4 , FC_6 , and FT_8 in *White*. In Fig. 9, *White* shows a significantly greater ERD in the spatial task (in the case of the ERD, positive t -test statistics indicate greater ERD in the spatial task).

3.3.4 β -Band ERD

In the beta-band ERD, the frontal area at F_7 , F_3 , F_1 , F_z , FC_5 , FC_3 , and C_3 showed significant differences between tasks (See Table 1). In Fig. 10(a), multiple comparisons testing of noises found significant differences between *NM*–*White* in the frontal area at AF_z , F_1 , F_z , FC_1 , and FC_z in the verbal task. Figure 10(b) shows significant differences found between tasks in the fronto-central area at F_3 , F_1 , F_z , F_2 , FC_5 , FC_3 , FC_1 , FC_2 , FC_4 , C_5 , and C_3 when presenting *NM*, and in the left prefrontal to frontal area at F_{p1} , AF_7 ,

β ERD

Fig. 10 Electrode positions indicating the locations of significant differences in beta-band event-related desynchronization (ERD; hatched circles) found in multiple comparisons testing ($p < 0.05$).

AF_z , F_7 , F_3 , FT_7 , and FC_3 , (also FT_8 and PO_8) when presenting *Brownian*. See Fig. 10(c).

Figure 11 quantitatively shows the t -test statistics averaged over the channels showing significant differences in Fig. 10. As shown in Fig. 11(a), the ERD was significantly greater in *White* than *NM* in the verbal task (in the case of the ERD, positive t -test statistics means greater ERD for *White*). In *NM* and *Brownian*, Figs. 11(b) and (c) show the ERD to be greater in the spatial task than in the verbal task (more than zero). In addition to these results, *Brownian* in Fig. 11(b) and *NM* in Fig. 11(c) were also significantly different in variance between tasks, as shown by averaging the t -test statistics over the channels showing significant differences for *NM* and *Brownian*, respectively.

4. Discussion

Figures 5(b) and 5(d) indicated that in the spatial task, the variance of the theta band was enhanced significantly with the ERS, with a peak latency of around 300 ms, when presenting *White*, and in the verbal task when presenting *Brownian*; furthermore, a significant difference in variance between tasks was also confirmed with *White* and *Brownian*. Notably, a frequency dependence of variance in the verbal task may exist, in that theta-band power decreased as the high-frequency component increased from *Brownian* to *White* (see Fig. 5(d)); there was a tendency towards the opposite effect in the spatial task, for which theta power decreased with decreasing high-frequency content, although *Brownian* showed no significant difference in tasks (see Fig. 5(b)). Moreover, the cortical region showing these tendencies was almost the same in both noises, namely the left frontal area (see Figs. 4(b) and (d)). Deiber

Fig. 11 Mean t -test statistics $\pm$ S.E. averaged over channels showing significant differences in beta-band event-related desynchronization (ERD) in Fig. 10. The horizontal line shows the level of significance for $p < 0.05$.

et. al. have suggested an association of attention level with theta reactivity in a working memory task [5]. In our previous ERP study [3], the reaction time was observed to be around 450 ms, from which the decision time for character matching in a match/no match task was estimated to be around 340 ms, when assuming about 110 ms for the motor response of button pressing [13]. This estimate suggests that a theta-band ERS around 300 ms is due to neural activity associated with character matching prior to a decision. Considering these findings, the *White* condition in the spatial task and the *Brownian* condition in the verbal task are suggested to activate a neural process reflected by the theta-band ERS, associated with allocation of attention to the character matching process, and dependent on the frequency characteristics of the ambient noise.

Spatial distributions for the channel locations showed the significant differences between tasks were inconsistent among noises, especially, for *NM* and *Pink*, only when changing the frequency component. It may be possible that activity related to *NM* and *Pink* was independent, and/or that specific neural activity among noises was not frequency de-

pendent for *White* and *Brownian*. However, further work is required to clarify these issues.

When presenting *NM* in the verbal task, the variance of the alpha band was enhanced significantly with the ERS, with a peak latency of around 190 ms in the fronto-central area (see Figs. 6 (a) and (b), and Figs. 7 (a) and (b)). In addition, a significant difference in variance between *NM* and *White* in the verbal task was noted, and between tasks for *NM* as well. Therefore, only *NM* may enhance neural activities underlying the alpha-band ERS exclusively. Considering the reaction time and the peak latency of the alpha-band ERS as well as the theta-band ERS, the alpha-band ERS may correlate with perception or cognition of the currently presented character, or with retrieval of previous characters needed for matching. Thus, in the verbal task, *NM* without amplitude modulation may enhance the perception or cognition of currently presented characters or retrieval of previous characters.

Figure 9 indicates that the variance of the alpha band in the spatial task decreases significantly with the ERD with a peak latency of around 500 ms when presenting only *White*. In addition, a significant difference in variance between tasks for *White* was also confirmed in a broad frontal area, as illustrated in Fig. 8. Pfurtscheller et. al. have suggested that alpha power decreases when neural activities increase [12]. Neural activity may have a close relationship with the effect of *White* on the alpha-band ERD in the spatial task. The reaction time data suggest that the alpha-band ERD may be associated with neural processes accompanying the storage of previous characters. Therefore, high frequencies may more strongly affect neural activities required for this storage in the spatial task, because *White* contained more of the high frequency component relative to the other noises.

Figure 11 (a) indicates that in the verbal task, the variance of the beta band decreased significantly with the ERD, with a peak latency of around 400 ms in the fronto-central area when presenting *White* versus *NM*, corresponding to presentation of most, and none, of the high frequency component, respectively. This result suggests that high frequency component in *White* may affect the neural activity of the verbal task underlying the beta-band ERD. Considering also the reaction time, high-frequency fluctuating noise may be affecting neural processes associated with the storage of previous characters, as well as the alpha-band ERD, or any processes occurring after character matching in the verbal task.

As seen in Figs. 11 (b) and 11 (c), the variance of the beta band decreased in the spatial task, rather than the verbal task, for *NM* and *Brownian*, the noises with little or no high frequency component. Notably, the noises enriched in the high frequency component, *White* and *Pink*, showed no difference between tasks. These results suggest that the lower the amount of higher frequency sound present (i.e., *NM* and *Brownian*), the greater the beta-band neural activity differs between the tasks. That is, more high frequency sound may alter the neural activities in the verbal task, whereas little or no high frequency sound may improve the neural responses

in the spatial task. It should be mentioned that a frequency dependency similar to that seen in theta-band ERS may exist in the beta-band ERD as well.

Our previous ERP study suggested that ambient noise with the high-frequency characteristics of white noise affected the function of attention associated with working memory in a spatial task [3]. This result is consistent with the effect *White* demonstrated on theta-band ERS activity in the spatial task used in the present study.

NM, *White*, and *Brownian* showed specific activities in this study. On the other hand, *Pink* showed no statistically significant specific activities. However, *Pink* showed a tendency towards affecting the theta-band ERS and beta-band ERD activities. The *Pink* noise high-frequency component ranged between that of *White* and *Brownian*, and consistently with this, it affected neural activity to a degree ranging between *White* and *Brownian*.

The results of this study begin to clarify how ambient noise affects neural activity, although they could not identify which ambient noises produced a positive effect on intellectual performance and which produced a negative effect. These questions provide fertile ground for future studies.

5. Conclusion

From the significant findings of this study, we conclude that fluctuating ambient noises affect oscillatory neural activities during cognitive tasks, at least those involving working memory such as the 3-back task. The frequency content of amplitude-modulated ambient noises may determine specific fluctuations in various EEG frequency bands; in particular, though, a frequency dependency may exist in the theta-band ERS and beta-band ERD responses. We also observed that the alpha-band ERS response in *NM* and the alpha-band ERD response in *White* enhanced neural activities associated with verbal and spatial mental operations on characters. Therefore, we suggest that changes in oscillatory neural activity can be used to evaluate a person's auditory environment. Although behavioral responses in terms of reaction time herein failed to indicate any differences among tasks or noises, it is important to emphasize that the results do suggest that an optimal ambient noise exists for each kind of intellectual activity.

References

- [1] K. Nakajima, S. Hashimoto, and Y. Tahara, "A study on psychophysiological effects of fluctuating sound environments," *J. Archit. Plann. Environ. Eng., AIJ*, no.480, pp.77–85, 1996 (in Japanese).
- [2] M. Otani, Y. Iwaya, M. Kobayashi, S. Yairi, Y. Suzuki, and T. Chiba, "Perceptual effect of ambient sound on 3D virtual sound space," *IEICE Technical Report*, EA-2009-51, 2009 (in Japanese).
- [3] S. Yasukawa, K. Kato, K. Suzuki, and A. Ishikawa, "Ambient noise effects on event-related potential during cognitive activation," *IEEE Transaction on Electronics, Information and Systems*, vol.134, no.2, pp.277–285, 2014 (in Japanese).
- [4] S. Watter, G.M. Geffen, and L.B. Geffen, "The n-back as a dual-task: P300 morphology under divided attention," *Psychophysiology*, vol.38, no.6, pp.998–1003, 2001.
- [5] M.-P. Deiber, P. Missonnier, O. Bertrand, G. Gold, L. Fazio-Costa, V. Ibañez, and P. Giannakopoulos, "Distinction between perceptual and attentional processing in working memory tasks: A study of phase-locked and induced oscillatory brain dynamics," *Journal of Cognitive Neuroscience*, vol.19, pp.158–172, 2007.
- [6] J. Kaiser, B. Rahm, and W. Lutzenberger, "Temporal dynamics of stimulus-specific gamma-band activity components during auditory short-term memory," *NeuroImage*, vol.44, no.1, pp.257–264, 2009.
- [7] E.M. Holz, M. Glennon, K. Predergast, and P. Sauseng, "Theta-gamma phase synchronization during memory matching in visual working memory," *NeuroImage*, vol.52, no.1, pp.326–335, 2010.
- [8] Q. Luo, D. Mitchell, X. Cheng, K. Mondillo, D. McCaffrey, T. Holroyd, F. Carver, R. Coppola, and J. Blair, "Visual awareness, emotion, and gamma band synchronization," *Cerebral Cortex*, vol.19, no.8, pp.1896–1904, 2009.
- [9] S. Ray, E. Niebur, S.S. Hsiao, A. Sinai, and N.E. Crone, "High-frequency gamma activity (80–150 Hz) is increased in human cortex during selective attention," *Clinical Neurophysiology*, vol.119, no.1, pp.116–133, 2008.
- [10] K. Kato and O. Miura, "Oscillatory neural activity associated with cognitive processes affected by spatial frequency," *IEEJ Transaction on Electrical and Electronic Engineering*, vol.9, no.3, pp.288–293, 2014.
- [11] G. Pfurtscheller G and F.H. Lopes da Silva, "Event-related EEG/MEG synchronization and desynchronization: basic principles," *Clinical Neurophysiology*, vol.110, no.11, pp.1842–1857, 1999.
- [12] M. Bastiaanse and P. Hagoort, "Event-induced theta responses as a window on the dynamics of memory," *Cortex*, vol.39, no.4-5, pp.967–992, 2003.
- [13] K. Kato, T. Kobayashi, and S. Kuriki, "Event-related potentials elicited by the alternation of perceived images in binocular rivalry," *Japanese Journal of Medical Engineering and Biological Engineering*, vol.36, no.2, pp.111–118, 1998 (in Japanese).

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