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Phase coherence of auditory steady-state response reflects the amount of cognitive workload in a modified *N*-back task

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ABSTRACT

The auditory steady-state response (ASSR) is an oscillatory brain activity evoked by repetitive auditory stimuli. Previous studies have reported that the power and phase locking index (PLI) of ASSR could be modulated by the degree of workload. However, those studies used different physical stimuli for tasks of differing difficulty, and the effect of the internal workload itself has not been clearly understood. In this study, we employed the modified *N*-back task as a visual working memory task in order to vary the degree of difficulty while keeping the physical stimulus constant. The experiment consisted of four types of tasks: No-Load (NL), 1-back, 2-back, and 3-back tasks. The auditory stimulus was a 40 Hz click sound to induce ASSR. Sixteen healthy subjects participated in the present study and magnetoencephalogram responses were recorded using a 148-channel magnetometer system. The hit rate decreased and the reaction time increased according to the task difficulty. Grand averaged phase coherence activities showed the 40 Hz ASSR reductions accompanying an increase in the task difficulty even with the identical external stimuli. In particular, the phase coherence activities in 3-back task were significantly lower than that in the NL and 1-back tasks. Our results suggest that the ASSR can be a useful indicator for the amount of workload in the brain.

1. Introduction

Mental workload, that is, the degree of workload in the brain is constantly changing in our daily life. Recent studies have shown the possibility that cognitive workload can be evaluated by using electroencephalography (EEG), and therefore, the evaluation of cognitive workload using brain activity is getting more attention. The method that is commonly used for evaluating the workload is by presenting task-irrelevant stimuli during the performance of the main task. The EEG study that employed a visuo-motor task with incrementally varied levels of difficulty showed that the amplitudes of some kinds of event related potentials (ERPs) caused by the task-irrelevant auditory stimuli were inversely related to task difficulty (Miller et al., 2011).

Evaluation of the cognitive workload in real environments such as evaluation of the elderly patient's state for health, and the crisis response ability of the driver while driving the car, is highly informative. In general, ERPs can be extracted from the averaged EEG data over many epochs in an electrically shielded room and movement-restricted condition since ERPs are transient activities caused by a stimulus. However, in real environments recording, artifacts such as electrical noise generated from the surrounding electronics, and electromyogram (EMG) generated by the motion of the user are technical problems. Therefore, it is not easy to extract ERPs from EEG data in real environments because of these artifacts.

To solve this issue, we focused on the auditory steady-state response (ASSR), which is the oscillatory brain activity evoked by repetitive auditory stimuli. Since ASSR continues while a stimulus is presented, the signal to noise ratio of ASSR is commonly higher than ERPs. Moreover, the frequency spectrum of ASSR shows a fine peak for the frequency of repetitive stimuli, in contrast to the relative broad spectrum of EMG. This makes it easy to separate ASSR and EMG.

ASSR is known to be evoked most strongly by a 40 Hz auditory stimulus (Galambos et al., 1981; Ross et al., 2000), and the source localizes in the primary auditory cortex (Engelien et al.,

Abbreviations: ASSR, auditory steady-state response; PLI, phase locking index; NL, no-Load; MEG, magnetoencephalogram; EEG, electroencephalography; ERP, event related potential; EMG, electromyogram; SNR, signal to noise ratio.

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2000; Gutschalk et al., 1999; Herdman et al., 2002; Kuriki et al., 1995; Pantev et al., 1996; Weisz et al., 2004). ASSR has been already used in auditory function research in psychiatric disorders and as the evaluation index for testing hearing sensitivity (Picton et al., 2003). Another study reported enhancement of ASSR with attention to auditory stimuli (Tiitinen et al., 1993). Moreover, recent studies have employed the ASSR to evaluate cognitive workload (Griskova et al., 2007, 2009; Griskova-Bulanova et al., 2011; Roth et al., 2013). These studies showed the possibility that ASSR is modulated by the workload; however, they used different physical stimuli for different workload conditions. Therefore, it is not clearly known whether the ASSR modulation is caused by the change in the cognitive mental workload or the change in the physical stimuli. If the modulation of ASSR is caused by cognitive workload change, ASSR can be a nice indicator to quantify the state of the mental workload. Additionally, previous studies compared the relationship between the workload and ASSR by using two types of difficulty. Therefore, it is unclear whether the ASSR is modulated gradually according to task difficulty.

In this study, we employed a modified *N*-back task in order to regulate the degree of difficulty within an identical visual stimulus. The *N*-back task is a continuous performance task that has been used in the study of short-term working memory (Owen et al., 2005), where it is possible to change the degree of cognitive workload by adjusting the number of load factor *N*, keeping the identical physical feature of the visual stimuli. In this study, we investigated the ASSR modulation caused by *N*-back tasks by adjusting the number of load factor N using magnetoencephalography (MEG).

2. Materials and methods

2.1. Participants

Sixteen healthy subjects (8 men and 8 women; age range, 20–23 years) participated in our experiments. All participants had normal hearing and normal or corrected-to-normal vision. Participants signed informed written consents after the details of the procedure had been explained. All experimental procedures were approved by the ethical committee of National Institute of Information and Communications Technology. MEG data from one participant was excluded from further analysis owing to artifacts resulting from a metallic material in his/her mouth.

2.2. Experimental procedure

Experimental stimuli were visual stimuli for performing the *N*-back task and repetitive auditory stimuli for inducing the ASSR. The visual stimulus presentation was controlled by Visage (Cambridge Research System, Rochester, UK) and presented on a screen using LCD projector (Canon, X700, JPN, frame rate: 60 Hz) in a magnetically-shielded dark room. Participants observed the screen from a supine position on a bed. The auditory repetitive stimuli were 40 Hz click sounds (sampling rate: 8192 Hz), transmitted to the participant via plastic tubes (Aero Corporation, US, EAR TONE 3A-10). The 40 Hz click sound consisted of a pulse width of 10 ms that was repeated every 25 ms. The peak sound pressure level of the auditory stimuli was 60.5 dB for the right ear and 61 dB for the left ear.

The schematic illustration of the visual stimuli is shown in Fig. 1. For 500 ms, “1” or “2” (50% for each) was randomly presented with randomly selected color (80% white and 20% red) in all experiments. A blank image with a fixation point was presented for 2000 ms between trials. One block consisted of four types of task: No-Load (NL), 1-back, 2-back, and 3-back tasks. In the NL task, participants

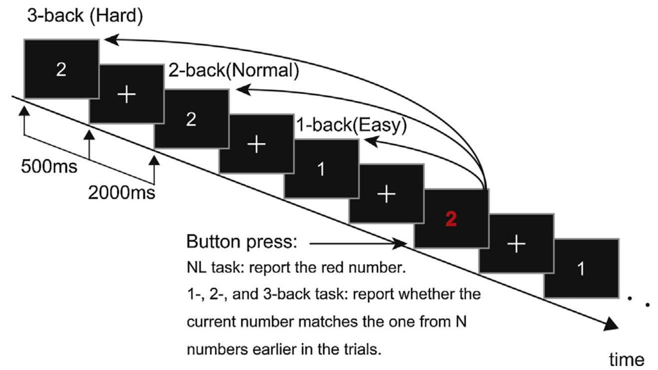

Fig. 1. Schematic representation of the experimental procedure: “1” or “2” (50% for each) was randomly presented for 500 ms with randomly selected color (80% white and 20% red) in all tasks. In the NL task, participants reported the number by pressing one of two buttons when the color of the stimulus is red. In the 1-, 2-, and 3-back tasks, participants performed *N*-back task and were asked to report whether the current number matches the one from *N* numbers earlier in the trials.

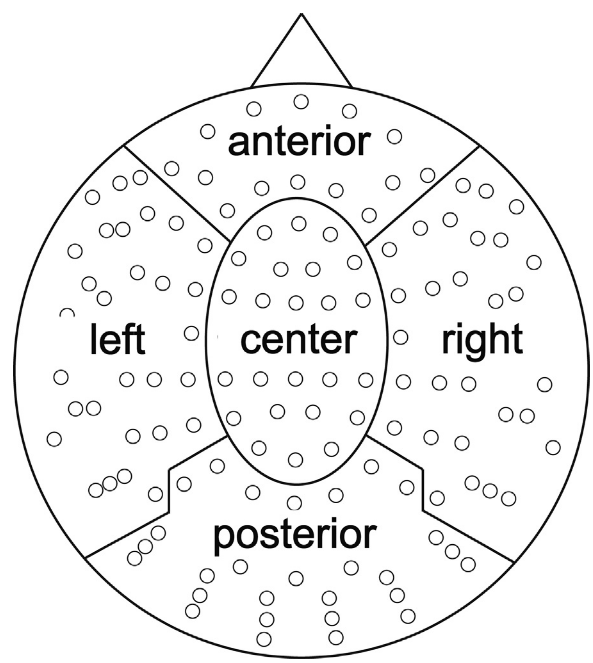

Fig. 2. The five regions (anterior, center, right, left, and posterior) defined by BTi (4-D neuroimaging).

reported the current number by pressing one of two buttons when the color of the stimulus was red. In the 1-, 2-, and 3-back tasks, participants performed the *N*-back task. They were asked to report whether the current number matches the one from *N* numbers earlier in the trials. The red colored number was not presented within five trials from the start of a task. The index or middle finger was used for button pressing, and the order of fingers was counterbalanced across participants. The experiment consisted of two blocks. Participants performed 100 trials of each task. The order of the task types was randomized in one block. After the first block, which consisted of a total of 400 trials, they performed the second block, which was constructed in the same way. The total number of the trials was 800 in the experiment. Auditory stimuli were presented to participants consistently while performing the tasks; however, they were instructed to ignore the auditory stimulus. All participants performed a practice test for about 20 min before the experiment.

MEG responses were measured using a 148-channel magnetometer system (BTi (4-D Neuroimaging), MAGNES2500WH, US),