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Electrophysiological measurement of interest during walking in a simulated environment

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ABSTRACT

A reliable neuroscientific technique for objectively estimating the degree of interest in a real environment is currently required in the research fields of neuroergonomics and neuroeconomics. Toward the development of such a technique, the present study explored electrophysiological measures that reflect an observer's interest in a nearly-real visual environment. Participants were asked to walk through a simulated shopping mall and the attractiveness of the shopping mall was manipulated by opening and closing the shutters of stores. During the walking task, participants were exposed to task-irrelevant auditory probes (two-stimulus oddball sequence). The results showed a smaller P2/early P3a component of task-irrelevant auditory event-related potentials and a larger lambda response of eye-fixation-related potentials in an interesting environment (i.e., open-shutter condition) than in a boring environment (i.e., closed-shutter condition); these findings can be reasonably explained by supposing that participants allocated more attentional resources to visual information in an interesting environment than in a boring environment, and thus residual attentional resources that could be allocated to task-irrelevant auditory probes were reduced. The P2/early P3a component and the lambda response may be useful measures of interest in a real visual environment.

1. Introduction

Over the past decade, the application of neuroscientific techniques has spread from a clinical field to engineering and economic fields (i.e., neuroergonomics and neuroeconomics). A major challenge in neuroergonomic and neuroeconomic studies is how to objectively estimate the mental state of a person in a real environment with neuroscientific techniques; such estimation in a real environment is very important, since cognitive processing in a real environment can be markedly different from that in a highly simplified environment (e.g., Mehta and Parasuraman, 2013). Previous works conducted from such a standpoint have demonstrated that electrophysiological measurements can be a powerful and useful technique for estimating the mental state; it has been well-established that event-related potentials (ERPs) for task-irrelevant probes can reflect an observer's mental workload during a cognitive task in real or nearly-real environments, such as a radar-monitoring task and a video-game task (Allison and Polich, 2008; Kramer, Trejo, and Humphrey, 1995; Miller, Rietschel, McDonald, and Hatfield, 2011; Sugimoto and Katayama, 2013; Ullsperger, Freude, and Erdmann, 2001). For example, Allison and Polich (2008) presented task-irrelevant auditory probes that should be ignored while the participant performed a video-game task, and showed that the amplitudes of multiple ERP components (P2, N2, and P3) elicited by the task-irrelevant auditory probes decreased with an increase in the difficulty of the video-game task. The results were interpreted in terms of the allocation of attentional resources to the video-game task or to the task-irrelevant auditory probe. Thus, based on the limited resource model (Kahneman, 1973), it was assumed that more attentional resources were required to perform the task when it was difficult and the resources available for allocation to auditory channel were reduced, which resulted in a decrease in ERP amplitudes in response to task-irrelevant auditory probes. Studies with the task-irrelevant probe technique have provided a clear demonstration of the suitability of electrophysiological measurement for estimating the mental state in real environments.

Emotions, such as interest, play an important role in economic decision-making and therefore their assessment is one of the main topics in neuroeconomic studies (Camerer, Loewenstein, and Prelec, 2005). "Interest" can be defined as a basic positive emotion, which is the central motivation for engagement in creative and constructive endeavors, and it is considered that interest can facilitate selective attention to particular objects, events, and goals (Izard, 2009). To our knowledge, few studies have examined the relationship between ERPs elicited by task-irrelevant probes and the degree of interest in the task. Given that the interest in a task modulates selective attention, as proposed by Izard (2009), it is reasonable to consider that more attentional resources would be allocated to the task if the participant was

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very interested, which should reduce the amount of resources available for allocation to task-irrelevant probes. Indeed, in previous studies that used the dual-task paradigm (i.e., participants were required to perform a secondary auditory task as well as a primary visual task), the amplitudes of ERPs in response to task-relevant auditory probes decreased with an increase in the observer's interest in the primary visual task (Rosenfeld, Bhat, Miltenberger, and Johnson, 1992; Suzuki, Nittono, and Hori, 2005). Thus, as in the dual-task paradigm, it is expected that the amplitudes of ERPs in response to task-irrelevant auditory probes would decrease when an observer is very interested in the visual task. The dual-task paradigm can be insufficient for estimating an observer's interest in the natural situation. Specifically, since observers are required to perform a secondary auditory task in the dual-task paradigm, the cognitive processing for the primary visual task may be disrupted and therefore interest in the primary visual task under the dual-task paradigm may be different from that in the same visual task under the single-task paradigm (i.e., when only performing a visual task).

The goal of the present study was to develop a task-irrelevant probe technique for estimating the observer's interest that can be adequately applied in a real environment, which should extend the usability of this technique in neuroeconomic examinations. To this end, we examined whether or not ERPs in response to auditory probes could reflect the observer's interest even when the auditory probes were completely task-irrelevant. ERPs in response to task-irrelevant auditory probes were measured while the participant walked through a simulated shopping mall; the recent development of immersive virtual reality technologies allows us to simulate extensive fields, and an observer can walk freely through such nearly-real fields by stepping in place (Ishikawa et al., 2013). The attractiveness of the shopping mall (i.e., the degree to which participants are interested in the shopping mall) was manipulated by opening and closing the shutters of stores. In the open-shutter condition, all of the stores were open and many articles could be seen on display in each store. In the closed-shutter condition, all shutters were closed and only the store signs could be seen. To obtain ERPs in response to task-irrelevant auditory probes, a two-stimulus oddball sequence that consisted of frequent standard and rare deviant stimuli was used. Since more attentional resources are expected to be allocated to visual information when an observer is interested in the shopping mall (Izard, 2009), the amplitudes of ERPs in response to task-irrelevant auditory probes should decrease in the interesting environment (i.e., open-shutter condition) relative to the boring environment (i.e., closed-shutter condition).

Caution should be exercised with regard to an inherent limitation in the use of the task-irrelevant probe technique. In terms of its application, the task-irrelevant auditory probe technique is advantageous in that it can be adapted to many kinds of visual tasks, and task-irrelevant auditory ERPs can be compared among tasks even if the visual intensities are different, since they are not phase-locked to visual stimuli. However, the task-irrelevant probe technique also has a disadvantage; i.e., task-irrelevant auditory ERPs do not directly reflect the increase in the allocation of attentional resources to the visual task, but rather reflect the decrease in the allocation of attentional resources to the task-irrelevant auditory probes. Thus, we must assume that the total amount of attentional resources available is constant. Consequently, task-irrelevant auditory ERPs are vulnerable to changes in the total amount of attentional resources, such as with a change in the level of arousal. To compensate for this disadvantage, in the present study, eye-fixation-related potentials (EFRPs) were also examined as a possible measure of interest in a visual environment. EFRP is a kind of ERP that can be obtained by averaging electroencephalographic (EEG) signals that are time-locked to the offset of saccadic eye-movements (i.e., the onset of fixation pauses). The most prominent component of EFRPs is referred to as the lambda response, which is a positive-going component with a peak at around 80 ms after the offset of saccadic eye-movements (Scott, Groethuysen, and Bickford, 1967). The lambda response is considered to reflect the processing of visual information at newly eye-fixated positions, and its neural source has been localized to the visual cortex (Kazai and Yagi, 2003).

It has been reported that the amplitude of the lambda response can vary with psychological factors, such as workload, fatigue, and attention to visual inputs (Takeda, Sugai, and Yagi, 2001; Takeda, Yoshitsugu, Itoh, and Kanamori, 2012; Yagi, 1981). For example, Takeda et al. (2001) demonstrated a positive correlation between accuracy in a visual cognitive task (i.e., a proof-reading task on a visual display terminal) and the amplitude of the lambda response, indicating that the amplitude of the lambda response reflected how closely the observer examined the visual information. At present, the relationship between the amplitude of the lambda response and the observer's interest is unclear, but it is reasonable to consider that more visual information is acquired when the observer is interested in the environment (see Izard, 2009), which results in an increase in the amplitude of the lambda response. Since the amplitude of the lambda response can vary not only due to psychological factors but also physical factors, such as illuminance and the contrast of visual stimuli (Gaarder, Krauskopf, Graf, Kropfl, and Armington, 1964; Yagi, Ishida, and Katayama, 1992), it is difficult to provide conclusive evidence for the observer's psychological state solely based on the lambda response if the visual environment is substantially different between conditions. We consider that task-irrelevant auditory ERPs and the lambda response of EFRPs can be mutually complementary measures of an observer's interest in the visual task. Specifically, we expected that the amplitude of the lambda response would show an opposite trend relative to the amplitudes of task-irrelevant auditory ERPs; the amplitude of the lambda response should be greater for the interesting environment (i.e., open-shutter condition) than for the boring environment (i.e., closed-shutter condition), whereas the amplitude of task-irrelevant auditory ERPs in the interesting environment should be less than that in the boring environment.

2. Method

2.1. Participants

Fourteen male university students (19–30 years old) participated in the present study. All participants had normal or corrected-to-normal vision, and had no difficulty in stepping to move in the simulated field. They were paid to participate in the experiment. Data from three participants were excluded from the analysis; two participants were excluded due to excessive noise synchronized with their stepping in the EEG signals (more than 65% of epochs contained artifacts beyond the ± 100 μV criterion) and one participant was excluded due to poor detection of his stepping. The present study was approved by the National Institute of Advanced Industrial Science and Technology (AIST) Safety and Ethics committee, and was conducted only after each of the participants had given their written informed consent.

2.2. Apparatus and stimuli

An immersive simulator was used in the present study (Fig. 1). In the simulator, the participant was surrounded by 24 liquid crystal displays (27-inch color) with an equilateral octagon-shaped column (8 way $\times$ 3 rows). The diagonal length of the simulator was 160 cm. The simulator can detect the direction of the participant's foot and his stepping every 33.3 ms by the use of RGB-D data from two ASUS Xtion sensors. Based on the detected foot direction and step, the participant could walk through the simulated environment omnidirectionally by stepping in place (moving distance was 60 cm per step). In this experiment, an actual shopping mall in the city of Tsukuba was simulated. All of the participants had been to the real shopping mall and were familiar with the original environment.

The task-irrelevant auditory oddball sequence was presented to measure ERPs. The standard stimulus was a 1000 Hz pure tone (approximately 90% of trials) and the deviant stimulus was an