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Electrophysiological evaluation of attention in drivers and passengers: Toward an understanding of drivers' attentional state in autonomous vehicles

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ABSTRACT

In order to safely use autonomous vehicle technologies, it is important to understand the state of drivers' attention as they ride in Level 3 self-driving vehicles, because they might be required to take manual control of the vehicle in certain situations. We assumed that the attentional state of a driver who has perfect confidence in a self-driving system, and as a result, who is unready to take control of the vehicle is similar to that of a passenger riding in a vehicle driven by another person. Therefore, we compared electrophysiological signals from drivers and passengers that were riding a vehicle in real road environments. Results indicated the following differences: (1) The number of small saccadic eye-movements was greater in drivers than in passengers, whereas the number of large saccadic eye-movements was greater in passengers than in drivers, indicating that passengers tended to look at information irrelevant to safe driving. (2) The amplitude of the P1 component of eye-fixation-related brain potentials time-locked to the offset of large saccadic eye-movements was greater in drivers than in passengers, indicating that visual information processing load was lower in passengers. (3) The duration of eye-blinks was longer in passengers than in drivers, indicating that the arousal level of passengers was relatively low. These findings suggest that these electrophysiological indices can be useful measures for evaluating the attention of drivers while riding in Level 3 autonomous vehicles. Possible differences in the attentional state between drivers and passengers are discussed.

1. Introduction

The development of autonomous vehicle technologies is expected to provide transportation methods that are more comfortable as well as safer, by preventing driver error accidents (Bishop, 2000). In the period before a fully driverless car is achieved, drivers will be required to step into take control of the vehicle in certain situations. This is Level 3 automation, as defined by the National Highway Traffic Safety Administration (2013). In Level 3 automation, for example, a driver can fully cede control of the vehicle when traveling on an expressway, but she or he has to take control of the vehicle when

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it leaves the expressway. For safe application of autonomous vehicle technologies at Level 3, it is important to understand the state of drivers' attention as they ride in such vehicles, because changing attentional state from passive riding to active driving has been shown to be difficult (Marinik et al., 2014). For example, simulated driving tasks have demonstrated that several tens of seconds are needed for the transition of a driver's attentional state from monitoring the driving of the autonomous vehicles to manual driving (Merat, Jamson, Lai, Daly, & Carsten, 2014). But because driving simulators cannot fully reproduce the demands encountered while driving in real road traffic environments (Caird & Horrey, 2011), the driver's attentional states can be significantly different under real and simulated environments. More specifically, although a number of studies of simulator validity have suggested that simulators can provide a valid tool for assessing driving behavior (Mullen, Charlton, Devlin, & Bédard, 2011), there is as yet no evidence that simulators can adequately assess the state of the driver's attention while riding in an autonomous vehicle (i.e., in a non-driving situation). Therefore, studies of real road environments are necessary to understand the actual state of drivers' attention. However, in the current development stage of autonomous vehicle technologies, it is difficult to examine safely the actual state of non-professional drivers as they ride in autonomous vehicles at Level 3 in a public roadway.

In this preliminary investigation for understanding the attentional state of drivers riding in Level 3 autonomous vehicles under real road environmental conditions, we assumed that the attentional state of a driver in a fully automated vehicle, who has perfect confidence in the self-driving system, would be similar to that of a passenger riding in a vehicle driven by another person. Based on this assumption, we compared attention-related electrophysiological signals of drivers and passengers that were traveling in the same vehicle, in order to ensure that drivers and passengers experienced the identical road environment. This was considered important because results of real road experiments might be contaminated by factors in the external environment, such as traffic density, road conditions, and the weather, which can accidentally vary from time to time, and are difficult to control between experimental conditions. Simultaneous measurement of electrophysiological signals from drivers and passengers was expected to provide a more precise evaluation of attentional states.

Attentional states of the driver and passenger in a Level 3 autonomous vehicle might differ to certain degree, depending on the driver's sense of confidence in the self-driving system, such that the attentional state of a driver with high confidence in the system might be similar to that of a passenger, whereas a driver with low confidence in the system might pay more attention to the driving environment than a typical passenger. Currently, there is no method of estimating the attentional state of non-professional drivers riding in autonomous vehicles traveling on public roadways, other than by comparing drivers and passengers riding conventional vehicles. Recently, Baltodano, Sibi, Martelaro, Gowda, and Ju (2015) proposed a procedure in which a passenger was considered a driver of an autonomous vehicle for investigating human interactions with autonomous vehicles. Of course, special care is necessary in the interpretation of results from such studies. Nevertheless, we believe that investigating the attentional state of passengers is a useful first step toward understanding drivers riding in Level 3 autonomous vehicles.

Three indices related to attention were investigated. First, the number of saccadic eye-movements was evaluated to examine the frequency of attention shifts. Saccadic eye-movements (or eye-fixations) are a common measure of drivers' attention (Crundall & Underwood, 2011). In automotive studies, video-based eye-monitoring systems are commonly used to evaluate saccadic eye-movements and fixations. Such systems can be successfully used to assess where drivers direct their attention. However, the electrooculogram (EOG) method, which measures differences in electrical potential from two electrodes placed near the eyes, is better able to detect small saccadic eye-movements with high temporal resolution. In the present study, we measured EOGs for evaluating the number of saccadic eye-movements. Although EOG data do not provide absolute eye-fixation positions, the number of saccadic eye-movements can provide useful information about how often participants acquire visual information from new locations.

Second, to determine how closely participants examined the visual information, we estimated the amplitude of the P1 component of eye-fixation-related brain potential (EFRP). The EFRP is a type of event-related brain potential that is obtained by averaging electroencephalographic (EEG) signals that are time-locked to the onset of fixation pauses (i.e., the offset of saccadic eye-movements). The P1 component of EFRP (previously called the lambda response, Scott, Groethuysen, & Bickford, 1967) is a positive-going component with a peak at around 80 ms after the offset of saccadic eye-movements, which is known to reflect visual attention to newly fixated positions (Takeda, Sugai, & Yagi, 2001; Yagi, 1981; Yagi, Sakamaki, & Takeda, 1997). For example, Takeda et al. (2001) demonstrated that P1 amplitude decreased with decreasing attention to a visual task, and behavioral performance was positively correlated with P1 amplitude. The EFRP is measurable by time-locking to voluntary saccadic eye-movements, which naturally occur during visual tasks, including simulated driving (Takeda, Yoshitsugu, Itoh, & Kanamori, 2012) and real road driving (Wiberg, Nilsson, Lindén, Svanberg, & Poom, 2015). The use of EFRP thus allows us to evaluate drivers' and passengers' attention under naturalistic driving environments without any additional stimuli or tasks.

Third, we also measured the duration of eye-blinks in order to assess the arousal level of drivers and passengers, because arousal level is closely related to attentional resource capacity (Kahneman, 1973). It has been well established that the duration of spontaneous eye-blinks increases with drowsiness (e.g., Caffier, Erdmann, & Ullsperger, 2003), and this index has been used in estimating drowsiness of drivers (Sugiyama et al., 1996).

In summary, the present study employed electrophysiological indices including the number of saccadic eye-movements, the P1 amplitude of EFRP, and the duration of eye-blinks that were acquired from drivers and passengers in a preliminary investigation of drivers' attentional state in Level 3 autonomous vehicles. It was assumed that the attentional state of drivers in Level 3 autonomous vehicles would be similar to the attentional state of passengers in typical vehicles. Based on this