An apparatus to measure stimulus-related and response-related visual evoked potential in a simulated driving scenario

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***Abstract*—The present study evaluated an apparatus to measure the P3 event-related potential (ERP) component generated from both stimulus-locked (eye gaze) averaging and response-locked (key press) averaging. The apparatus used photographs of road sign related driving scenes as visual stimuli, and a customised EEG, eye tracking, and keyboard synchronised system. The results embraced a wider range of reaction time variation compared to similar work in the literature. In addition, the images used in this study include more complexity which explains the difference. The current experiment setup can reconstruct the P3 component using the response-locked averaging. This is then compared with the stimulus-locked averaging and a strong correlation is shown between the two approaches. This shows that response-locked averaging can be utilised as a sufficient tool to identify driver's visual stimuli registration in the brain. This observation may reduce the requirement for eye tracking in some future studies.**

Keywords—EEG, Event-related potential, P3, Stimulus-locked averaging, Response-locked averaging, Road signs, Distraction.

I. INTRODUCTION

Driver distraction is a leading cause of car accidents both nationally and internationally. The national Road Safety Authority (RSA) reported 148 fatalities on Irish roads in 2020 and 22,660 people lost their lives on the EU road in 2019 [1, 2]. Among them, 20-30% of all road collisions involve distraction [3]. Similar statistics can also be found in the National Highway Traffic safety administration (NHTSA) [4]. Driver distraction is defined as the diversion of attention away from activities critical for safe driving toward a competing activity [5]. The cause of distraction can be generally classified into two categories, visual distraction and cognitive distraction. Visual stimuli devoted to cognitive response is investigated in this study.

To better understand driver distraction, many research studies on advanced technologies of driver distraction measurement has been shown in the past decade, including the two most popular techniques, eye tracking (ET) and electroencephalography (EEG). EEG has some great advantages that allow researchers to perform cognitive studies, such as high temporal resolution, non-invasive, and no risk. Almahasneh *et al.* found an increased EEG amplitude when driving involved a secondary task, it significantly affected driving performance and the judgment capability [6]. Savage *et al.* investigated perceptual and cognitive load impacted on slowing of hazard response times, and increasing frontal lobe activity [7]. Distraction studies can also be assessed by event-related potential (ERP). In the present study, ERP is used to measure the driver's cognitive response to a specific visual event. ERP can be found in most visuo-motor tasks [8]. The ERP was extracted and averaged from the EEG using a number of time-locked signals. These events usually trigger sensory responses or motor responses. Such response captured by EEG can shed some insights into brain activities.

To extract the signals that are of interest requires event markers. The most common event marker used in EEG epoch extraction is the stimulus onset event. In stimulus-locked averaged ERP, a series of underlying components are elicited in sequence (e.g. P1, N1, P2, N2, and P3). The P3 component normally elicited between 300 ms to 800 ms after stimulus onset. The P3 component is typically elicited as a maximal signal by an unexpected target stimulus in the oddball paradigm [9]. In some studies, the P3 component can be subdivided into P3a and P3b. The P3a has been often found at the frontal lobe [10], but the P3b at the central-parietal lobe [9] and occipital lobe [11]. P3a is associated with working memory and often to be found after distraction stimuli in a three-stimulus paradigm [12]. Several research studies found distracter stimuli elicited the P3a and target stimuli elicited a P3b component [10]. The P3a component classically displays a frontal-central maximum. Typically, it has a relatively short peak latency, and habitually rapidly compares to P3b [13]. The P3b was related to the stimulus context updating process, memory storage, and attentional resource allocation [13]. In the present study, P3b is referred to as P3 (or P300).

The other signal extraction method is based on the reaction of the participant, called response-locked ERPs. As its name stated, the response locked ERP is often found in the study of motor control or movement related task and self-paced motor activity. The response-locked ERPs are used to analyse the readiness potential [14] and motor potential (MP) [15]. Verleger *et al.* explored the link between perceptual processing and response preparation using P3b amplitude measurement in stimulus-locked averages and response-locked averages [16]. Amenedo *et al.* investigated the relation of inhibition of return (IOR) in healthy young and older participants using the stimulus-locked and response-locked averaging [17]. Berchicci *et al.* compared components between the stimulus-locked and response-locked averaging with simple response task and discriminative visuo-motor task [18]. They found prefrontal N1, prefrontal P1, post-stimulus N1, post-stimulus P1 and P2 components were larger in stimulus-locked averaging than response-locked

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averaging. The N2 component was enhanced by response-locked averaging in a simple task, but not a discriminative task. The P3 component has peak amplitude larger in response-locked averaging than in the stimulus-locked averaging. The P3 showed slower peak latency in the discriminative task than in the simple task [18].

In the present study, more complex and realistic road sign related nature scenes were used as visual stimuli. We applied the response-locked averaging to reproduce the P3 component which was originally produced from the stimulus-locked averaging. The demonstration of the effectiveness of response-locked averaging showed an alternative solution for the detection of visual stimuli registration within the brain.

II. Methods

A. Participants

Fourteen healthy adults volunteered in this experiment, one participant (ID: 13) was excluded from the analysis due to incomplete data recording. The participants consisted of 9 males and 4 females, all right-handed. The age range was from 24 to 55 years (mean = 36.2). All participants were free of past or present neurological or psychiatric conditions and with normal or correct to normal visual acuity. The ethics committee of the university approved the experimental protocol.

B. Stimuli and apparatus

This experiment used three types of images (target images, non-target images, distraction images). All images were taken from a 4K resolution camera on Irish roads. There were 52 target images containing one single speed sign, which has a white background, road circle and a number in it (Fig. 1). There were 78 distraction images containing a road sign that is not a speed sign. There were 500 non-target images containing no road signs at all. All images were presented to the participants using the same random sequence at 1 Hz by the software Psychopy (1.85.2) running under Windows 7 on a PC with a 19-inch computer monitor. The monitor was set to the highest refresh rate, 75 Hz. The Psychopy generated software triggers that correspond to the image type and send out to the recording application.

C. Procedures

All three types of demonstration images were shown to the participants prior to the experiment starting so as to let the participants become familiar with the experiment. The experiment took place in a light dimmed, sound-attenuated, and radio frequency shielded room. The participants were seated on a comfortable chair in front of the computer monitor about 70 cm away. The participants were asked to press the space bar on a keyboard when the participants saw a speed sign in the presented image (target stimuli) as soon as possible, and no action to perform for the other two types of images (distractor stimuli and non-target stimuli). Upon starting the experiment, all instructions were presented on the screen again to remind the participants. Then a fixation cross showed at the centre of the screen for 2 seconds to set down eye gaze movement, then the experiment started. Each target or distractor road sign within the image varied in size from 0.5 degrees to 2.5 degrees and randomly appeared on either side of the road to prevent participants from making inferences about the road sign position on the following image presentation.

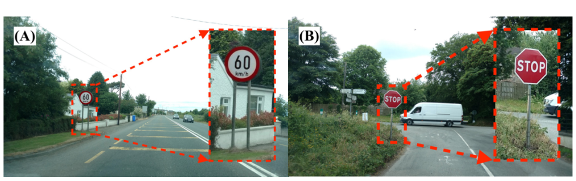

Fig. 1. Examples of stimulus images. (A) One example of target images. (B) One example of distraction images.

Each participant completed one run in a single recording session. The duration of one run was about 10 minutes. Three data streams were recorded for each participant during the experiment, EEG data, eye tracking data, and keypress reaction time.

D. Data recording

The EEG data were recorded from a 16 active electrodes mounted cap using the g.Tec g.USBamp at a sampling rate of 512 Hz. The electrode locations followed the 10-20 system montage (Cz, Pz, Oz, AF4, F3, F4, FC5, FC6, F7, F8, T7, T8, P7, P8, O1, O2) [19]. The ground electrode was FCz. The reference was at the left earlobes. In the experiment, the electrode impedance was measured and maintained under 5 kiloohms using a conductive gel. The participants were asked to keep still as possible as they could to minimise the movement artefact.

Eye movements were recorded with a portable Tobii X-120 eye tracking system. For calibration, we used nine points falling in the centre, four corners, and the mid-points of the four sides of the screen. The eye tracker was used in binocular node with data recording sampling rate at 120 Hz in each eye.

Syncrhonisation of the EEG recording and the eye movement data (as well as key press reaction time and stimulus image triggers) was achieved by using a previously developed data acquisition system with lab streaming layer (LSL) [20].

E. Data analysis

EEG data are processed offline using EEGLAB (v14.1.1). The data is first filtered with a finite impulse response filter at 0.16 Hz to 30 Hz to remove DC and high frequency noise. Infomax independent component analysis is used to remove eye blink, eye movement and facial muscle movement artefacts [21]. The continuous data is extracted by stimulus-locked and response-locked. For the stimulus-locked epochs, the epochs are extracted from -200 ms to 800 ms with respect to stimulus onset. Each epoch then is baseline corrected from -200 ms to 0 ms preceding stimulus onset. An automatic epoch rejection is used to remove epochs that the voltage potential exceeded ±75 μV. For the target trials that participants who missed key press are excluded. For the distraction and non-target trials that participants had pressed key are excluded. The epoch will also be excluded if the participant's gaze points never detected in the area of interest (AOI) for target and distraction trials. For the response-locked epochs, we follow the method from [22], the epochs are extracted from -800 ms to 200 ms with respect to response onset. Each epoch is baseline corrected from -800 ms to -600 ms. For ERP component analysis, we measure the P3 component from the parietal region at the Pz electrode. The peak amplitude of P3 is calculated at the time window 300 ms to 800 ms.

Statistical analysis is used to evaluate the stimulus-locked ERPs between the target stimuli produced P3 and distraction stimuli produced P3 using one-way analysis of variance (ANOVA) for peak amplitude and peak latency as factors ($\alpha = 0.05$). Pearson's correlation is used to assess the two waveforms of grand average ERPs for target stimuli ERP and distraction stimuli ERP, and the P3 ERPs produced by stimulus-locked averaging and response-locked averaging.

For the eye-gaze movement analysis, we first define the AOI within every target and distractor images by manually find the centre coordinates of the road sign and add 32 pixels distance to the radius of the road sign to draw a circle as our AOI. We also define the time of gaze point first detected in the AOI as the time of the gaze locked event.

III. Results

A. *Behaviour analysis*

Data from the thirteen participants who contributed to the ERP results are used for behavioural analysis. Anticipations, misses, and incorrect responses are excluded from the reaction time (RT) analysis. Outliers (outside two standard deviations of the mean) are excluded. The median response time is 627 ms, and the mean (± standard deviation) is 639 ± 107 ms. All participants have an average of 98.24% correct detection of the target trials, an average of 7.16% incorrect detection of the distraction trials and non-target trials. Only the trials with the correct response are used for further analysis.

B. *ERP analysis with stimulus-locked averaging*

Fig. 2 shows ERP plots from each individual participant at the channel Pz, each plot presents the averaged ERP waveform elicited from target stimuli (red line), distraction stimuli (blue line) and non-target stimuli (green line). The y-axis represents the stimulus-onset. Participant 4 and 11, which shows larger P3 in distraction stimuli than target stimuli. Except participant 4 and 11, the P3 peak amplitude of target stimuli has a range between 4.62 μV to 15.87 μV. The P3 peak amplitude of distraction stimuli has a range between 3.24 μV to 8.72 μV. The P3 peak amplitude of target stimuli is significantly larger than distraction stimuli in all participants, $F(1, 20) = 19.23$; $p < 0.001$. The P3 peak latency of target stimuli varies between 450 ms to 710 ms. The P3 peak latency of distraction stimuli varies between 330 ms to 630 ms. The P3 peak latency of target stimuli is longer than distraction stimuli in all participants, $F(1, 20) = 4.11$; $p < 0.05$. The averaged ERP of non-target stimuli presents without the P3 component. There are some advantages to explore the data from the individual participant. For instance, in participant 11, a clear observation shows in the figure, labelled as novelty P3 (P3a) and normal P3b.

Fig. 3 shows the grand average topography plots across three types of stimuli. The grand averaging analysis will eliminate some weak features, but can enhance the strong features across individual participants. The topographical distribution measures at the time point of the Pz maximum difference between three types of stimuli. During the visual searching process, a similar pattern is generated for all three

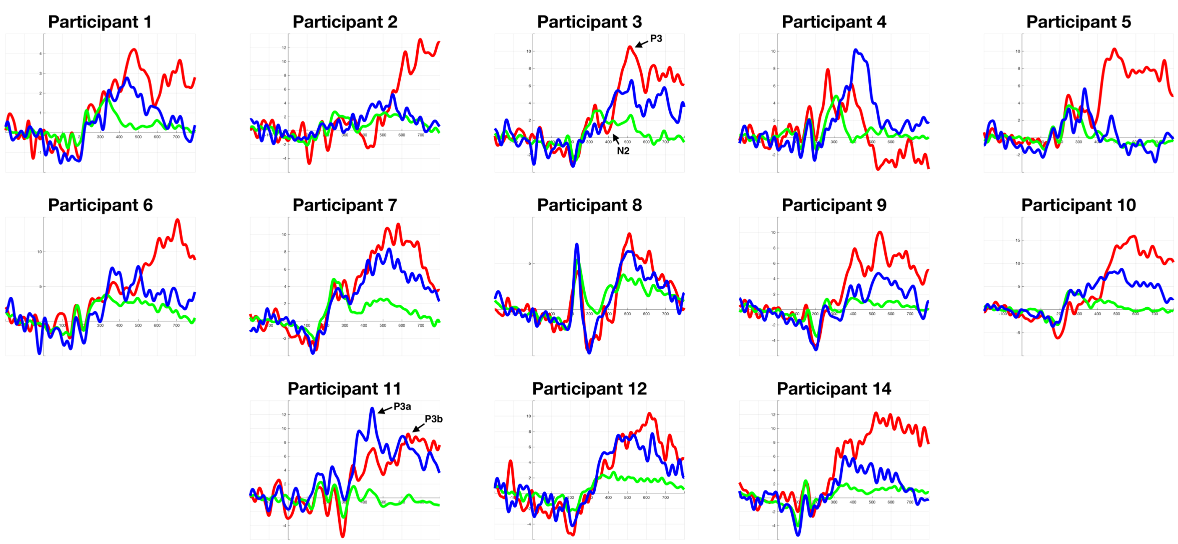

Fig. 2. Stimulus-locked averaged ERPs of target, distraction and non-target trials for each individual participant at the Pz channel location. Target ERP in red, distraction ERP in blue, non-target ERP in green. X-axis represents the time in milliseconds, Y-axis represents the voltage potential in micro-vols.

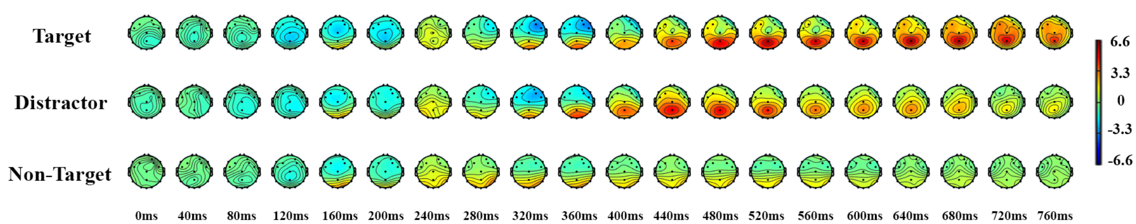

Fig. 3. Grand averaged ERP in 2-D topography plots. Top row is grand averaged ERP for target stimuli, middle row is grand average ERP for distraction stimuli, bottom row is grand average ERP for non-target stimuli.

types of stimuli in the first 240 ms following the image onset, a similar pattern is generated for targets and distractors in the first 320 ms following the image onset. We observe an evoked P1 component at the occipital site around 160 ms followed by a positive P2 component at the occipital site 360 ms [23]. Conversely, a late potential shows a large difference between categorising target and distractor. The target stimuli elicits a P3 component at peak latency around 520 ms, but the distractors elicit a P3 component at peak latency around 440 ms. The averaged ERP waveform of the target images has a stronger potential of P3 component compared to the distraction images, the non-target images do not obtain a P3 waveform. We calculate the correlation coefficient between the averaged ERP waveform of the target images and the averaged ERP waveform of the distraction images. The outcome shows that the correlation coefficient r = 8.756, reveals a positive strong correlation between the two waveforms.

C. *ERP analysis with response-locked averaging*

Fig. 4 shows the comparison plots between the stimulus-locked averaging (red line) and the response-locked averaging (black line) on the Pz channel. The amplitudes of the P3 component obtained by response-locked averaging are slightly stronger than the ones obtained by stimulus-locked averaging, except participant 7 and 9. The statistical analysis in Table 1 excludes participant 4, since no significant P3 component is observed in the stimulus-locked averaging. Table 1 shows the comparison between peak amplitude of the P3 component retrieved by stimulus-locked averaging and response-locked averaging. The correlation between stimulus-locked averaging and response-locked averaging for each participant is also calculated in Table 1. Nine out of twelve participants' data show a strong positive correlation between stimulus-locked averaging and response-locked averaging. The rest three participants show a moderate positive correlation. We further investigate the data of participant 3 and 4. For participant 3, we observe a strong positive correlation (r = 0.89, lag = 29.30 ms) after modifying the epoch extraction period of response-locked averaging from -800 ms to 200 ms to -900 ms to 100 ms related to response onset. For participant 4, we obtain a strong positive correlation (r = 0.85, lag = 0 ms) after modifying the epoch extraction period of response-locked averaging from -800 ms to 200 ms to -700 ms to 300 ms related to response onset. By simply manipulating the phase shift of response-locked averaging, we retrieve a strong correlation for all participants. This analysis shows that the response-locked averaging can reconstruct the P3 component as well as the stimulus-locked averaging.

IV. DISCUSSION

A. *Distractor P3a*

The present study is designed to evaluate a new customised driver cognitive response testing system to investigate the cognitive difference between driver response to a correct target and an incorrect target. Our results demonstrate that the P3 component measured from a distraction stimuli elicited ERP has a similar structure as

Table 1 Summary of P3 peak amplitude, difference of peak latencies and correlation between the stimulus-locked and response-locked averaging.

ID	Peak amplitude (μV) Stimulus -locked	Peak amplitude (μV) Response -locked	Difference of Peak latency (ms)	Correlation r	Correlation lags (ms)
1	4.03	5.41	-138.67	0.60	-95.70
2	13.21	18.32	68.36	0.89	0.00
3	10.52	11.72	105.47	0.57	-128.91
5	10.27	12.19	-37.11	0.91	9.77
6	14.64	17.18	140.63	0.82	-58.59
7	11.20	11.05	23.44	0.95	-19.53
8	6.88	9.00	-111.33	0.51	99.61
9	9.28	7.93	-46.88	0.85	-62.50
10	15.42	17.67	29.30	0.96	0.00
11	9.46	12.98	33.20	0.85	-21.48
12	10.37	14.31	5.86	0.91	3.91
14	12.50	13.57	-44.92	0.93	0.00

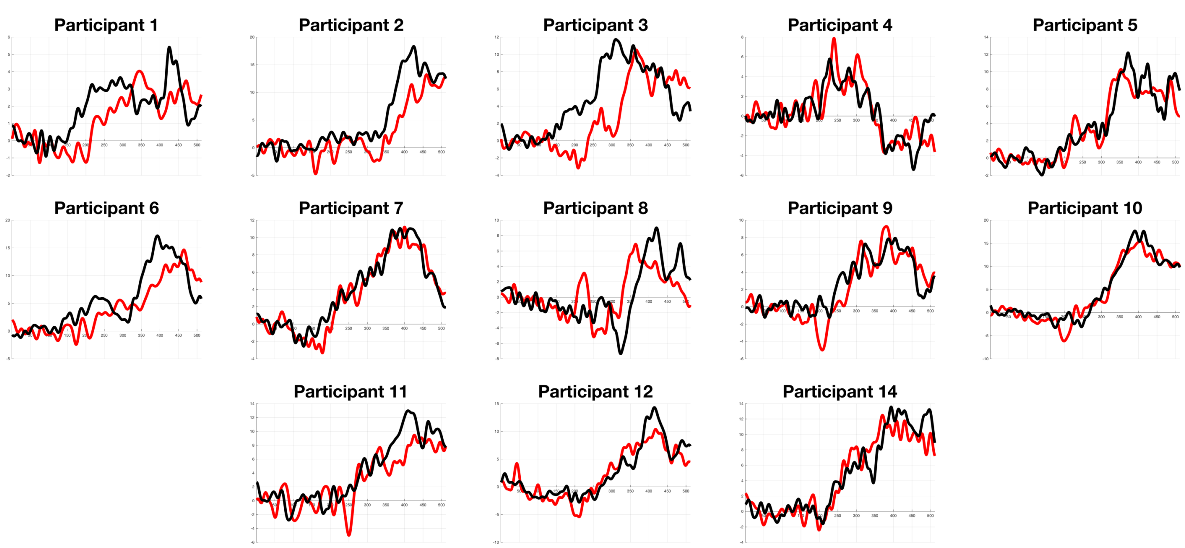

Fig. 4. Comparison of ERP plots obtained at Pz channel location between stimulus-locked averaging and response-locked averaging for each individual participant. Stimulus-locked ERP in red, response-locked ERP in black.

measured from target stimuli elicited ERP. But the waveforms might be distinguished by the difference in amplitude and latency. Our result is consistent with previous studies from Katayama and Polich, which in both 3-stimulus visual task and auditory task, the target stimuli produced the largest P3, the infrequent distraction stimuli produced less strong but highly similar to the P3 component [24]. Also in another study, Jeon and Polich conducted a 3-stimulus visual oddball experiment extended the work from Katayama and Polich to assess the distractor P3a in both active and passive conditions [10]. Their study reported the distractor P3a was elicited with similar amplitude and latency patterns for both the passive and active tasks [10]. In the present study, only participant 11 has a similar structure as stated in the literature. On the other hand, the major generators of P3a in the frontal cortex have been demonstrated in multiple research studies [12, 13, 25]. The measurement of distractor stimuli in the central-partial lobe may not be a good suggestion of the quality of the P3a, but it is well-accepted as an indicator of the detection of the distractor.

B. *ERP reconstruction from response-locked averaging*

In the correlation analysis between the stimulus-locked averaging and the response-locked averaging for each individual participant, the phase shift is varied, it can be positive, negative or zero phase shift. If it is assumed the response-locked averaging can perfectly reconstruct the stimulus-locked averaging with a given onset time, then the phase shift variation appears may be due to the inaccurate onset time for epoch extraction when carrying out response-locked averaging. Therefore, the chosen epoch time limits for response-locked averaging are non-trivial. Berchicci *et al.* chose 27 participants from 140 with low inter-individual RT variation (within 0.5 standard deviations) to compare the stimulus-locked averaging and the response-locked averaging [18]. In their study, they defined the epoch length with a much larger time window, and a baseline correction far from stimulus onset. The same procedure does not work in the present study, since the reaction time has a much bigger variation compared to that found in the literature. The present study shows the response related P3 peak amplitude is well correlated with stimulus related P3, which is also consistent with the literature [18]. Both the current study and the literature show P1 and N1 are masked in the response-locked averaging. As an indicator of cognitive registration from visual stimuli in the brain, the present work can produce an appropriate P3 component using the response-locked averaging on a set of realistic road sign related images.

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