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Evaluation of 3D Cognitive Fatigue Using Heart-Brain Synchronization

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Abstract

The purpose of this study was to identify an evaluation method for 3D cognitive fatigue based on a heart-brain synchronization phenomenon known as the heartbeat evoked potential (HEP). Thirty undergraduate students (15 females) watched a video in both 2D and 3D for an hour. Because visual fatigue is related to cognitive load, the HEP was used as an indicator of communication between the heart and the brain and therefore of cognitive function; responses were compared after 2D and 3D viewing. At the standard EEG sites F3 and F4, the alpha activity of the first and second HEP components was significantly increased after 3D video viewing relative to 2D. This increase likely indicates that sensory input from 3D video requires heavy computation by the brain, stimulating heart activity. The conclusion is that the first and second HEP components are significant parameters that can quantitatively evaluate 3D visual fatigue. Further work is needed to uncover the cause of 3D visual fatigue.

Keywords—3D Visual Fatigue, Cognitive Load, HEP (Heartbeat Evoked Potential), ERP (Event Related Potential), Heart-Brain Synchronization.

1. Introduction

In recent years, the interest in the 3D industry has increased due to the prevalence of 3D movies and television. As 3D provides additional visual depth over 2D, viewers prefer 3D content because of the experience of seeing motion in the depth dimension (Lambooij *et al*., 2007; Lambooij *et al*., 2009). Nonetheless, not all viewers benefit from 3D content. The major concerns related to 3D include 3D visual fatigue and visually induced motion sickness and remain unresolved. Specifically, 3D visual fatigue has been widely reported by viewers (Lambooij *et al*., 2009; Mun *et al*., 2012; Park *et al*., 2014). Therefore, a major challenge faced by the 3D industry is to understand and resolve problems related to 3D visual fatigue in order to improve the 3D viewing experience (Lee *et al*., 2010; Park *et al*., 2014).

To resolve this problem, an accurate and robust method for measuring 3D visual fatigue must be identified. Previous work has proposed that 3D visual fatigue is caused by factors such as age, anisopia, viewing distance, cross talk, and camera setting (Park *et al*., 2011; Mun *et al*., 2012; Park *et al*., 2014). Consequently, several studies have tried to measure 3D visual fatigue using self-reports (Yano *et al*., 2002; Takahashi, 2006), physiological signals (Trejo *et al*., 2006; Park *et al*., 2011; Kim and Lee, 2011; Sakamoto *et al*., 2012; Mun *et al*., 2012; Park *et al*., 2014), and visual capacity (Lee *et al*., 2009; Lee *et al*., 2010). However, at present there is no standardized method known to be best for evaluating 3D visual fatigue quantitatively. The cited methods have the drawbacks of lack of objectivity, use of only a single bio-parameter, and use of non-standardized performance thresholds, respectively.

Recently, several studies have suggested that 3D visual fatigue is related more to the degradation of human visual performance than to visual discomfort (Li *et al*., 2008; Lambooij *et al*., 2009; Mun *et al*., 2012; Park *et al*., 2014). While 3D content involves depth information, 2D content does not. During cognitive processing of 3D depth, the 3D content causes symptoms related to degradation of the visual system because of sensory overload, compared to 2D content (Lambooij *et al*., 2009; Mun *et al*., 2012; Park *et al*., 2014). In other words, the 3D visual fatigue is the brain strain which is the cognitive fatigue.

In previous studies, the cognitive fatigue (e.g., mental workload) was defined as decay of information processing capacity or resources (Gopher and Donchin, 1986; Kramer *et al*., 1987; Eggemeier *et al*., 1991). The cognitive fatigue has generally been evaluated by three measures such as self-assessment or subjective rating scales, performance measures (task measures) and psychophysiological measures (Eggemeier *et al*., 1991).

Cognitive fatigue has subjectively been scored according to the predefined questionnaires and described by interview techniques (Cain, 2007). Its questionnaires includes SWAT (Subjective Workload Assessment Technique), NASA task load index (TLX) and DRAWS (Defence Research Agency Workload Scale). SWAT has assessed mental workload based on three dimensions that were consisted of time load, mental effort load, and psychological stress load (Reid and Nygren, 1988). TLX has assessed mental workload of six components that were mental demand, physical demand, temporal demand, performance, effort, and frustration, with 21 scales (Hart and Staveland, 1988). (3) DRAWS has evaluated workload consisted of input demand (the acquisition of information from external sources), central demand (mental operations), output demand (the responses required by the task), and time pressure (rate at which tasks must be performed) from zero (no load) to 100 (full load) (Farmer *et al*., 1995). The subjective measures were depended on the personal interpretations and experience (Cain, 2007). Since their interpretation has been individual difference, the repeatability and validity of subjective evaluation has sometimes been uncertain and inappropriate (Annett, 2002; Cain, 2007). There has been finings that subjective measure was suited for judgment and decision making, but not for assessment of physical performance or mechanical performance (Vidulich, 1988; Yeh and Wickens, 1988).

Performance has been assessed by measuring the operator's information processing capacity based on task speed, error rate, and response time as indicator of mental workload (Cain, 2007). Therefore, the state of mental workload has been related to performance ability to allocate sufficient processing resources during the task (Matthews and Desmond, 2002; Smit *et al*., 2004). The performance has been reported to be deteriorated with mental fatigue (Lorist *et al*., 2000; Lorist *et al*., 2005, Boksem *et al*., 2005; Kato *et al*., 2009; Langner *et al*., 2010). The performance has relatively been easy and simple to be measured as mental workload. However, its measure has been lack of scientific robustness and ecological validity (Cain, 2007). [Also, the performance measures are required the task to assess the operator's performance. During the suffering of mental workload cannot be assessed, that is not suited for real-time procedure.

Psychophysiological measures has been objective method to assess mental workload defined as physiological state based on psychological processes, rather than performance and subjective rating measures (Wickens, 1992). The ERP (Event-related Potential) has been the most representative of psychophysiological measures. The P300 component of ERP was related to neuroelectric activity of cognitive function in brain such as attention, immediate memory, and arousal (Polich and Kok, 1995). Many previous studies reported that the person who experienced mental workload has decreased amplitude of P300 components and increased latency of P300 components in comparison with normal state (Wilson and O'Donnell, 1988; Ullsperger *et al*., 1988; Wickens, 1992; Boksem *et al*., 2005; Baldwin and Coyne, 2005; Kato *et al*., 2009). The ERP was the brain response caused by a single stimulus or event of interest (target and non-target) (Coles and Rugg, 1996). It is required the task to assess the operator's neural resource. Analogous to performance measures, it is not suited for real-time procedure.

In 3D visual fatigue terms, several studies reported that 3D visual fatigue could be measured with event related potentials (ERPs) (Li *et al*., 2008; Mun *et al*., 2012). When people become fatigued, they usually have trouble in focusing their attention, and ERP components (e.g., P100, P300, and P700) exhibit changes in amplitude and/or latency, reflecting diminished neuronal resources (Boksem *et al*., 2006; Martin and Garfield, 2006; Li *et al*., 2008; Toffanin *et al*., 2009). In these studies, ERP latency was increased in the visually fatigued state, an effect that was seen at standardized EEG electrode sites named P6 (Li *et al*., 2008) and P7 (Mun *et al*., 2012). These studies identified ERP latency as a useful quantitative indicator of 3D visual fatigue.

However, because demanding cognitive processes require greater brain activity and thus greater blood and oxygen supply, the heart is also implicated in such processes, suggesting a possible heart-brain synchronization. Moreover, sensory inputs from the environment alter heart rate and force via the autonomic nervous system, and then the heart sends a signal to the brain through afferent pathways encoding a rate of change of heart rate and blood pressure. The signal from the heart reaches the nucleus of the tractus solitarius, which then signals the cortex. In other words, the signal from the heart has an effect on brain sensory processing (the heart-brain coherence mode), and this is related to emotional stress, cognitive functions, and performance (McCraty and Watkins, 1996; Hansen *et al*., 2003; McCraty *et al*., 2009). Therefore, the evaluation of cognitive function can benefit from measuring heart-brain synchronization rather than only the brain response. In previous study, we found that the heart rhythm pattern was irregular rhythm and the autonomic balance was high activity of sympathetic nerves with irregular balance. It also had great effect on cognitive function (response time and performance in human brain) (Park *et al*., 2014). The heartbeat-evoked potential (HEP) can be adopted for measuring cognitive function quantitatively.

2. Research Purpose and Plan

The purpose of this study was to evaluate a method for measuring 3D cognitive fatigue based on the HEP. The HEP technique exploits the phenomenon of heart-brain synchronization. In order to evaluate 3D cognitive fatigue, the first and second HEP components (defined in II.) recorded during viewing of 2D content were compared with those recorded during viewing of 3D content.

The effect of the HEP on the 3D visual fatigue in this study was compared with one of the MTMM (Multitrait-Multimethod) analysis. The MTMM has verified the relationship between multiple-trait and multiple-method analyzing monotrait-monomethod diagonal, monotrait-heteromethod diagonal, and heterotrait-monomethod triangles of MTMM matrix. Its monotrait-monomethod diagonal has represented test-retest reliability obtaining higher coefficient of the variable for higher reliability. The monotrait-heteromethod diagonal has represented convergent validity shown by consistent correlation coefficient (r) of single trait with different methods. The heterotrait-monomethod triangles has represented discriminant validity showing degree of interrelationship between other traits with same method (Campbell and Fiske, 1959). Traits has studied in this research included the subjective evaluation, performance, and electrophysiology measures (HEP and ERP) in the 2D and 3D viewing conditions. The present study has been attempted to identify reliability of HEP for 3D visual fatigue measurement based on test-retest reliability, discriminant and convergent validity of MTMM method.

3. Theory of heart-brain synchronization

The HEP is characteristic change of brain waves (alpha activity) which can be occurred by changing cardiac output such as blood pressure, heart rhythm, and variability (Schandry and Montoya, 1996). Some visceral nerve (known as “vagus nervous”) transmits visceral-afferent information from major organ such as the heart into the brain (hypothalamic and thalamic nuclei, amygdalae, hippocampus, cerebellum, somatosensory cortex, prefrontal cortex, and insula) (Montoya *et al*., 1993). The visceral-afferent information was integrated at NTS (nucleus tractus solitarius) in the brainstem before reaching to the cortex, then the integrated information is transmitted to the mid-brain such as the hypothalamic and the thalamic (Jaening, 1996). The components of mid-brain exchange information with neocortex, especially frontal and prefrontal brain cortex. Because prefrontal and frontal cortex receive information directly through the visceral afferent pathways from hypothalamus and the thalamus, some researchers focused on the premotor and the orbital areas of the frontal lobe (Fuster, 1980; Nauta and Feirtag, 1986; Nieuwenhuys *et al*., 1988). These areas are related with attention and mental processes (Boussaoud, 2001; Hartikainen and Robert, 2003). Based on the relation between brain EP (evoked potential) component caused by heartbeat and the attention, significant post-R-wave (250 ~ 450 ms) in Fz brain region was reported (Schandry *et al*., 1986). In the other study, significant change in HEP was founded a negative shift of the waveform range 250 ~ 400 ms at Fz, F7, F8, and Cz brain regions (Schandry and Weitkunat, 1990). The HEP phenomenon can be considered for estimating the cortical activity such as attention and mental state by measuring synchronization between brain and heart (Fukushima *et al*., 2011). As shown in Fig. 1, the HEP is a phenomenon arising from the heart and brain becoming synchronized through afferent pathways in the vagus nerve. When the R-peak of the heart occurs, the electroencephalography (EEG) signal simultaneously displays a large negative-going peak due to synchronization of the heart and brain. This response has been previously characterized as the brain ERP and has been related to the first and second periods of the HEP (McCraty *et al*., 2009).

The first period of the HEP (50–250 ms after the R-peak) indicates the time interval required to transmit the information of "rate of change" from the heart to the brain, and is related to processing along the afferent pathway. When brain processing increases, thus increasing communication between the heart and the brain, synchronization in the alpha band is increased and indicates increased processing by the afferent pathway (Wölk *et al*., 1989; McCraty *et al*., 2009). The second period of the HEP (250–600 ms after R-peak) reflects transmission of both afferent signals and the hydraulic blood pressure wave from the heart to the brain. The second period of the HEP is also related to alpha synchronization. The increase of the alpha wave in the first period indicates an active state of afferent processing of cardiovascular information (Wölk *et al*., 1989; McCraty *et al*., 2009). The HEP first and second components are shown in Fig. 2.

4. Methods

4.1. Participants

Thirty undergraduate students (15 females), ranging in age from 20 to 28 years old (mean 24.1 ± 3.1) participated in the experiment. Each subject participated voluntarily and was paid $95.01. All participants had normal or corrected-to-normal vision (vision over 0.8) and were right-handed. They had no family or medical history related to cardiovascular or central nervous system diseases. Written informed consent was obtained from each subject prior to the experiment. In addition, participants were required to abstain from alcohol, cigarettes, and caffeine for 12 h prior to the experiment, and to get a full night's sleep. All protocols used in this study were approved by the Institutional Review Board of the Sangmyung University, Seoul, South Korea.

4.2. Experimental procedure

The participants watched a video in 2D and 3D. On the first day, they watched either the 3D or the 2D version of the video and on the next day they watched the video in the other dimensionality (e.g., first day 3D, second day 2D; order randomized across subjects). The viewing content was the same "movie" in both 2D and 3D versions from the movie "Step-Up" (Summit Entertainment, Touchstone Pictures, 2010). The 2D and 3D versions were presented on a 40-inch LED-3DTV (UN40ES6800F, Samsung) using a 3D Blu-ray Disc player (BD-ES6000, Samsung).

Participants watched the videos for an hour at a viewing distance of 1.68 m from the screen (corresponding to 3 H, where H is the height of the screen, i.e., 0.56 m). The viewing distance was in the range recommended by the 3DC Safety Guidelines for Dissemination of Human-friendly 3D, namely 3 H to 6 H. The setup of the experimental environment is shown in Fig. 3. The participants were required to self-report subjective visual discomfort both before and after the viewing. The subjective evaluation (four five-point scales) comprised four independent factors: visual stress (VS), eye pain (EP), body pain (BP), and image blurring factor (IBF) (Li, 2010). The participants also performed a cognitive task (see below) for about 15 min, both before and after the viewing. The experimental process is shown in Fig. 4. Experimental procedure of all participants was recorded using camera in order to monitor their attitude and faithfulness.

A stimulator was designed to measure cognitive fatigue. The design incorporated a technique validated in a previous study (Mun *et al*., 2012; Park *et al*., 2014), in which the visual fatigue caused by background flicker during measurement of the steady-state visual evoked potential was excluded to minimize contamination of the desired signal. The stimulus comprised presentations of alphanumeric characters randomly drawn from the set A-K + 5 or P, with a new draw at each presentation. One of the characters was the target character and was randomly repeated three times in a task. The other characters were the distractors. Successive presentations were separated by two seconds. The target "5" was included among the distractors with an average probability of 0.05. One trial consisted of 5 sequences involving 60 alphanumeric characters with a length of 10 seconds (trial interval: 2 seconds). One block was consisted of 5 trials, and total task was repeated 15 times. The interval between targets was below one seconds in order to avoid overlapping ERPs (data separation problem). Details of the stimulator are shown in Fig. 5. The participants were asked to detect a target "5" flickering at a rate of 6 Hz and to signal this by pressing a space bar with minimal delay. Reaction times between 200 ms and 1200 ms after target onset were considered as valid responses for further analysis. The EEG and electrooculography (EOG) data collected during target presentation following the bar press constituted the input to the ERP analysis.

4.3. Data Acquisition & signal Processing

EEG, electrocardiography (ECG), and EOG signals were recorded both before and after each viewing. EEG signals were recorded from eight channels on the scalp at positions F3, F4, C3, C4, P3, P4, O1, and O2 based on the international "10–20" system. The reference and ground were based on Cz and FAz, and the electrode impedance was kept below 5 kΩ. ECG signals were recorded through one channel with the lead-I method. EOG signals were recorded from two channels, the vertical and the horizontal, to permit removal of the blinking artifact. These signals were recorded using an amplifier system (ECG 100C, EOG 100C, and EEG 100C amplifiers in BIOPAC system Inc., USA) and digitized with the DAQ-Board (NI-DAQ-Pad9205 in National Instrument Inc., USA) at a rate of 500 Hz.

The HEP extraction steps were as follows. (1) The R-peak was detected in the ECG signal based on the QRS detection algorithm (Pan and Tompkins, 1985). (2) Then the EEG signals were extracted from a specific range (the period from 0–600 ms after R-peak) based on the R-peak timing. (3) The blinking artifacts were removed from the extracted signals based on the vertical and horizontal EOG signals. (4) The next step combined the extracted EEG signals across all trials using the "grand average technique." (5) Signals were then classified into the two components of interest—the first period (50–250 ms after the R-peak) and the second period (250–600 ms after the R-peak). (6) Each period was processed using a fast Fourier transform (FFT) and the power in the alpha band was extracted (Wölk *et al*., 1989; McCraty *et al*., 2009). In addition, ERP latency was extracted using the same method as in a previous study (Mun *et al*., 2012). Blinking artifact was removed using AcqKnowledge v4.1 software (BIOPAC system Inc., USA), and signal processing was processed using LabVIEW2010 (National Instruments Inc., USA). Signal processing is shown in Fig. 6.

4.4. Statistical analysis

This experiment was designed to test the viewer's experience between 2D and 3D conditions "within subjects." However, to compare 2D and 3D conditions in any other way would be difficult owing to scatter in the reference states. Either t-tests or Mann- To compensate counteract problem caused by multiple comparison, Bonferroni correction was performed for the derived statistical significances (Dunnett, 1995). Statistical significant level was controlled based on number of each individual hypothesis (i.e., $\alpha = .05/n$). Statistical significant level of each measure set up .0125 (subjective evaluation, $\alpha = .05/4$), .005 (performance and ERP, $\alpha = .05/10$), and .003125 (HEP, $\alpha = .05/16$), respectively. The effect size based on Cohen's *d* (parametric) and absolute value of *r* (non-parametric) were also calculated to confirm practical significance. In the case of Cohen's *d*, standard values of 0.10, 0.25, and 0.40 for effect size are generally regarded as small, medium, and large, respectively. In the case of *r*, standard values of 0.10, 0.30, and 0.50 for effect size are generally regarded as small, medium, and large, respectively. In addition, to verify test-retest reliability, convergent validity, and discriminant validity among various 3D cognitive fatigue measures such as subjective evaluation, ERP, and HEP, MTMM matrix was used. If the attribute of data samples is multitrait and multimethod, the MTMM matrix confirms the relationship between multiple measures. By confirming monomethod-monotrait (reliability diagonal), monomethod-heterotrait, and heteromethod-monotrait, the test-retest reliability, discriminant validity, and convergent validity can be verified, respectively (Campbell and Fiske, 1959).

5. Results

5.1. Viewing contents

In our experiment, 2D and 3D video as visual stimuli have totally same contents, because they are just 2D and 3D versions of same movie as shown in Fig. 7. In our previous researches, we already validated visual strain caused by low level features of the filmic content such as spatial (luminance, color, visual activity, etc.) and temporal characteristics (e.g., average shot length, temporal shot structure, movement dynamics, etc.) (Lee and Park, 2009; Lee *et al*., 2009). To validate whether difference of low level features between 2D and 3D video is being or not, the features were quantitatively measured by using methods of our previous works (Lee and Park, 2009; Lee *et al*., 2009).

Firstly, spatial features such as brightness (represented as 0 ~ 255), contrast (standard deviation of 8 bits gray image), saturation (represented as 0 ~ 255), and hue (0□ ~ 360□) were calculated. For fair comparison, frames of 2D version were horizontally reduced in half, and then the reduced frame was compared with the left image of the corresponding 3D frame. From both 2D and 3D videos, the spatial features were almost same with difference at decimal. Next, temporal features such as edge difference and scene change frequency were compared. The size normalization policy is same with the one at the mentioned comparing spatial features. At results, there is no variation of temporal features between 2D and 3D videos. Consequently, our used 2D and 3D visual stimuli has no difference except for cognized depth.

5.2. Subjective evaluation

As shown in Fig. 8, the subjective evaluation scores in the 3D viewing condition were significantly increased compared to the 2D viewing condition for EP ($t(28) = –3.230$, $p = 0.003$, Cohen's $d = 1.220$), BP ($t(28) = –3.963$, $p = 0.001$, Cohen's $d = 1.498$), and IBP ($t(28) = –4.122$, $p = 0.000$, Cohen's $d = 1.558$). No significant effect was found for the VS component ($t(28) = –2.635$, $p = 0.014$, Cohen's $d = 0.996$).

5.3. Performance

The performance measurements include accuracy and reaction time for given targets. As shown in Fig. 9, the accuracy in the 3D viewing condition were significantly decreased compared to the 2D viewing condition ($t(28) = 3.318$, $p = 0.003$, Cohen’s $d = 1.254$). And the reaction time in the 3D viewing condition were significantly increased compared to the 2D viewing condition ($t(28) = -4.132$, $p = 0.000$, Cohen’s $d = 1.562$).

5.4. ERP latency

Mann-Whitney test showed that ERP latency in the 3D viewing condition was significantly longer compared to that in the 2D viewing condition in regions P4 ($Z = –3.842$, $p = 0.000$, $r = 0.701$), O1 ($Z = –3.908$, $p = 0.000$, $r = 0.713$), and O2 ($Z = –4.002$, $p = 0.000$, $r = 0.731$). As shown in Fig. 10, no significant effects were found for the other brain regions (F3, F4, C3, C4, and P3). Significant ERP latency increases were detected in P600 at P4 ($M = 35.14$ ms, $SD = 21.17$), O1 ($M = 27.57$ ms, $SD = 25.27$), and O2 ($M = 47.00$ ms, $SD = 32.64$).

5.5. HEP

As shown in Fig. 11, for the first and second HEP components, a Mann-Whitney test showed that the first HEP component was significantly increased in the 3D viewing condition compared to the 2D viewing condition in regions F3 ($Z = –3.002$, $p = 0.002$, $r = 0.548$) and F4 ($Z = –3.262$, $p = 0.001$, $r = 0.560$). No significant effects were found for the other brain regions (C3, C4, P3, P4, O1, and O2).

Moreover, the second HEP component during the 3D viewing condition was significantly increased compared to the 2D viewing condition in regions F3 ($Z = –4.457$, $p = 0.000$, $r = 0.814$) and F4 ($Z = –4.181$, $p = 0.000$, $r = 0.763$). No significant effects were found for the other brain regions (C3, C4, P3, P4, O1, and O2).

5.6. MTMM Matrix

In our experiment, multi-method was used such as 2D and 3D viewing conditions. Also, multi-trait was measured as visual fatigue such as the subjective evaluation (EP, BP, and IBF), ERP (latency of brain region at P4, O1, and O2), and HEP (alpha activity of HEP first and second components of brain region at F3 and F4) based on statistical significance measures. The detailed results of the correlation analysis are shown in Table 1. Retest reliability can be verified by the main diagonal of MTMM correlation matrix between 2D and 3D viewing test. The subjective measures (SE_{EP}, SE_{BP}, and SE_{IBF}) are shown good reliability for the 2D viewing test (.74, .72, and .77). In the 3D viewing test, SE_{BP} and SE_{IBF} also are shown good reliability (.71 and .75), but SE_{EP} was not satisfactory (.65). The performance measures (P_A and P_{RT}) are shown an unsatisfied reliability in both 2D and 3D viewing test (2D: .66 and .68, 3D: .48 and .54). The ERP latency at P4, O1, and O2 regions is shown good reliability for the 3D viewing test (.79, .75, and .72), but it was not satisfactory in the 2D viewing test (.66, .67, and .66). The HEP first components latency at F3 and F4 regions are shown good reliability in both 2D and 3D viewing test (2D: .75 and .76, 3D: .82 and .79). The HEP second components latency at F3 and F4 regions are shown very good reliability in both 2D and 3D viewing test (2D: .84 and .89, 3D: .92 and .94). Also, the reliability coefficients between 2D and 3D viewing test are internally consistent in HEP measures rather than other measures.

Discriminant validity can be verified by the heterotrait-monomethod triangles. In the heterotrait-monomethod triangles, correlation coefficients between HEP and ERP measures have a significant relationships (.40 ~ .99). Especially, correlation coefficients between HEP second component (F3 and F4 regions) and ERP latency (O1 region) are shown a strong positive correlation (.60 ~ .99 In contrast, correlation coefficients between HEP and other measures have been relatively low (.06 ~ .39) compared to ERP measures. Correlation coefficients between ERP and other measures have also been relatively low (.07 ~ .51). The discriminant validity was not robust between ERP and HEP measures. Convergent validity can be verified by the monotrait-heteromethod (validity diagonal). The HEP measure have a higher correlation (.71 ~ .77) rather than other measures (SE: .32 ~ .47, P: .32 ~ .37, ERP: .46 ~ .66).

6. Discussion

3D visual fatigue has been major obstacle to the development of the 3D industry. In order to resolve this problem, research is needed to determine the best way to measure and quantify visual fatigue in order to evaluate proposed improvements in 3D technology. The purpose of this study was to test an evaluation method for 3D cognitive fatigue based on the alpha power of the first and second HEP components.

In order to confirm visual fatigue in both 2D and 3D conditions, 3D visual fatigue was first evaluated using a subjective evaluation and ERP latency analysis based on previous studies. Following subjective evaluation, the participants claimed to experience visual fatigue after watching a 3D video, but not after watching a 2D video.

This result is consistent with previous studies (Yano *et al*., 2002; Park *et al*., 2011; Park *et al*., 2014). However, our subjective evaluation method for measuring visual strain (mental workload) was not well-accepted and extensively validated (i.e., DSSQ, dundee stress state questionnaire). This problem will be solved through our further research. ERP latency measurements showed that cognitive load on the participants was greater after 3D viewing. Increases in cognitive load led to the viewer experiencing difficulty in focusing their attention on the cognitive ERP task and being easily distracted. Some studies have suggested that 3D visual fatigue is related to the degradation of human visual function rather than simple visual discomfort. Viewing 3D content requires viewers to use more cognitive resources for processing 3D information compared to 2D content. Thus, 3D content might cause 3D symptoms that may reduce the cognitive capacity of individuals for processing relatively sophisticated visual information (Li *et al*., 2008; Lambooij *et al*., 2009; Toffanin *et al*., 2009). This implies that eyestrain is really brain strain, indicating cumulative cognitive load. Because of this relationship, 3D visual fatigue could be measured using ERP (Li *et al*., 2008; Mun *et al*., 2012) and this finding was confirmed in the present study.

As mentioned earlier, subjective evaluations and ERP latencies confirmed that the present experimental design succeeded in producing visual fatigue. In addition, the main finding of significant effects of the first and second HEP components was confirmed.

First, the alpha power of the first HEP component was significantly increased in the F3 and F4 regions after watching a 3D video. The first HEP component indicates the time interval required for the information of "rate of change" in the heart to travel to the brain through afferent pathways in the vagus nerve (Wölk *et al*., 1989; McCraty *et al*., 2009). Thus, the increase of alpha power (first HEP component) indicates increased communication from the heart to the brain. Following the "poly-vagal theory," the cognitive processing of sensory input was not characterized through the EEG but through heart-brain synchronization (Porges, 2007; Porges, 2011; Cherland, 2012). A great deal of research supports this theory (Porges, 1972; Sokolov, 1963; Darwin, 1998; Porges, 2011). Therefore, during 3D video viewing, brain fatigue leads to degradation of the human visual system.

Second, the alpha power of the second HEP component was significantly increased, also in the F3 and F4 regions, after watching a 3D video, relative to the 2D data. The second HEP component represents the time interval required for the blood pressure wave to transmit from the heart to the brain in parallel with late signaling in afferent pathways in the vagus nerve (Wölk *et al*., 1989; McCraty *et al*., 2009). The increase of alpha power (second HEP component) suggests that the brain was making heavy demands on the heart. If the pressure wave was rapidly transmitted to the brain to supplement the first HEP component, it meant that the brain was especially activated by cognitive processing of sensory input. Again, this result supports the idea that 3D visual fatigue is brain strain and therefore cognitive fatigue (Li *et al*., 2008; Mun *et al*., 2012). In addition, the results suggest the idea that the 3D visual fatigue or visual discomfort was caused by a low level of attentional focusing ability, which in turn led to increased cognitive load. This is consistent with previous studies on ERP (Li *et al*., 2008; Mun *et al*., 2012). Because ERP measurement requires stimulation by a visual target that is incompatible with the fatigue-inducing tests, real-time fatigue evaluation is not possible. However, because the HEP exploits heart-brain synchronization, specifically synchronization between heart rhythm and brain alpha rhythm, the HEP can evaluate processing-related fatigue in real time.

In the MTMM matrix result, the HEP measure showed high reliability rather than other measures, and was internally consistent in both 2D and 3D viewing condition. This result shows that HEP measure has stronger reliability of repeated measure compared to other measures. Generally, electrophysiology measures showed high reliability rather than non-electrophysiology such as performance and subjective rating. Although there has been different in method, HEP measure has consistently showed consistently high correlation while the other measures have not. Specially, subjective evaluation and performance measures showed significant discrepancy. Therefore, HEP measure has shown high reproducibility and convergent validity. Correlation coefficients between HEP and ERP measures showed strong correlation. However, correlation coefficients between HEP and other measures were low and same were found for ERP. The correlation between HEP second components (F3 and F4 brain region) and ERP latency at O1 region was quite high. Discriminant validity identified that non-electrophysiology measures was relevant to other measures, but not on electrophysiology measures. In contrast to non-electrophysiology measures, discriminant validity between ERP and HEP did not identify the relevant relationship. ERP is well known indicator of cognitive function related to mental work load (Boksem *et al*., 2006; Martin and Garfield, 2006; Li *et al*., 2008; Toffanin *et al*., 2009; Mun *et al*., 2012). High correlation between HEP and ERP measures indicates the validity of HEP measure as indicator of cognitive function. Prior studies on HEP validated the usage of the measurement as indicator of cognitive function (McCraty and Watkins, 1996; Hansen *et al*., 2003; McCraty *et al*., 2009). Low discriminant validity between HEP and ERP represented that they were highly correlated with HEP measures having higher reliability than ERP measures. Higher test-retest reliability and convergent validity of HEP were compared with one of non-electrophysiology measures. The results showed superiority of HEP than ERP on assessment of 3D visual fatigue. Therefore, measurements of the first and second HEP components are recommended as better quantitative evaluators of 3D visual fatigue than ERP measures.

However, neither the first nor the second HEP component was significantly different after 3D vs. 2D viewing in any brain region, save regions F3 and F4. Consistently with this, the heart-brain synchronization channel directly connects through afferent pathways from the vagal complex to the prefrontal and frontal cortices (McCraty *et al*., 2009). A previous study reported that the heart's afferent input to the brain modulates activity in the frontal cortex, and that both changed with a change in the heart rhythm (Lane *et al*., 2001). In the present study, heart-brain synchronization dependencies on viewing technology were not confirmed in brain regions other than frontal. In addition, depth perception processing requires the optic chiasm to fuse the images from the left and right eyes, and the chiasm is located in the frontal area (Blakemore, 1970; Lepore *et al*., 1986; Standing *et al*., 2005). In light of this, it is proposed that the perception of a 3D stereoscopic image activates the frontal cortex and can overload the visual pathway. Also, spatial and temporal features of filmic content may strongly affect to visual strain. However, our research focuses on the comparison between 2D and 3D contents. Therefore, we tried to quantitatively validate no difference between 2D and 3D videos in terms of low level features. In our future works, we will consider the mentioned low level features as parameters in terms of 3D visual strain and its comparison with 2D one.

7. Conclusion

The purpose of this study was to identify an evaluation method for 3D cognitive fatigue based on the heart-brain synchronization signal known as the HEP. When participants experienced visual fatigue, the alpha power of the first and second HEP components increased. 3D visual fatigue was related to cognitive load and activation of frontal cortical areas (F3 and F4 regions). Measuring the first and second HEP components may be useful for quantitatively determining 3D visual fatigue. In addition, because the HEP can be used to measure real-time 3D visual fatigue, the method has an advantage over offline methods. Taken together, the results suggest that HEP measurements can be used to determine causes of 3D visual fatigue such as viewer characteristics, visual content, viewing environment, display, and device factors, as well as to validate improvements in 3D technologies.

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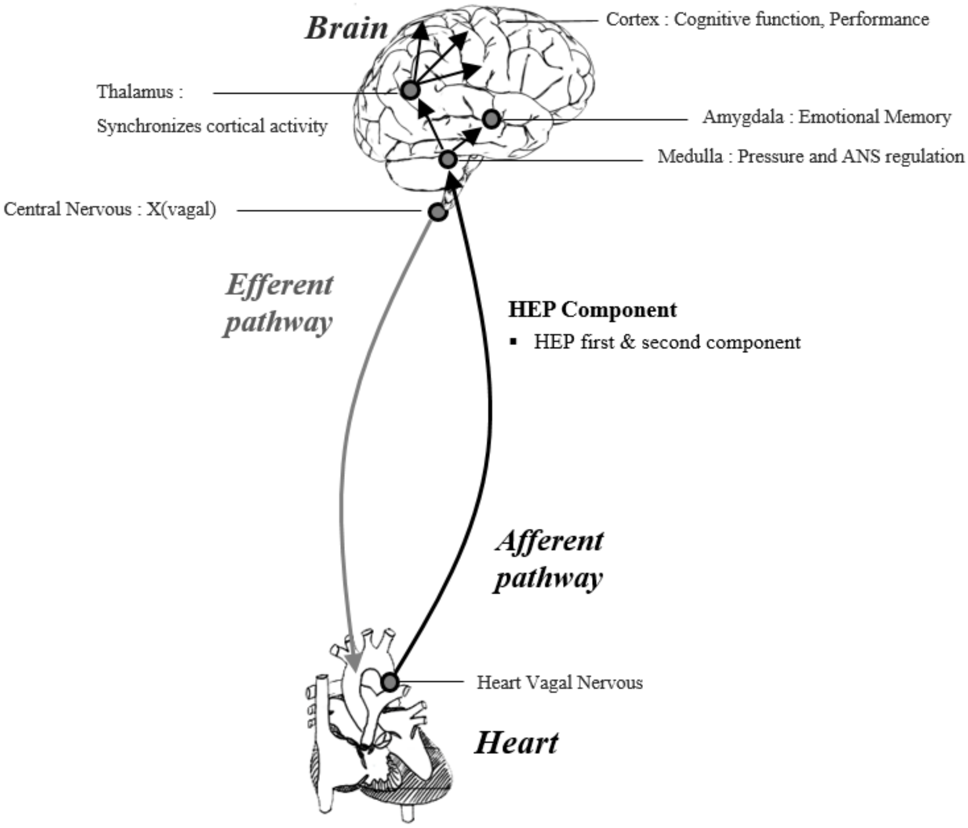

Fig. 1. Theory behind heart-brain synchronization by afferent pathway and HEP components. The heart transmits the information of "rate of change" (e.g., heart rhythm, heart rate, blood pressure) from the heart to the brain.

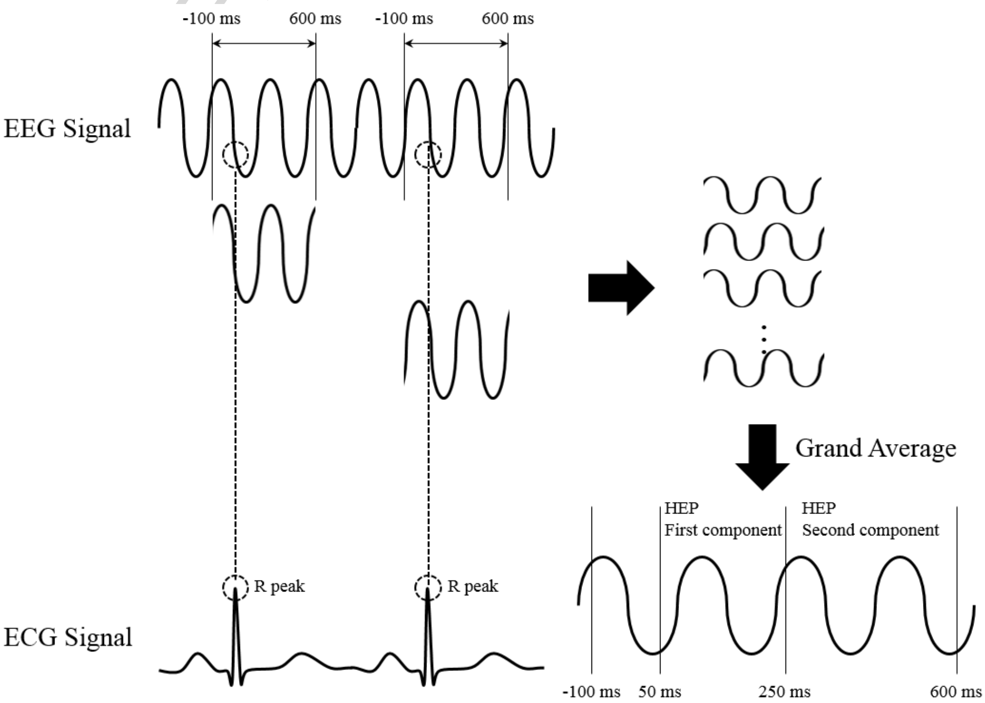

Fig. 2. First & Second HEP components.

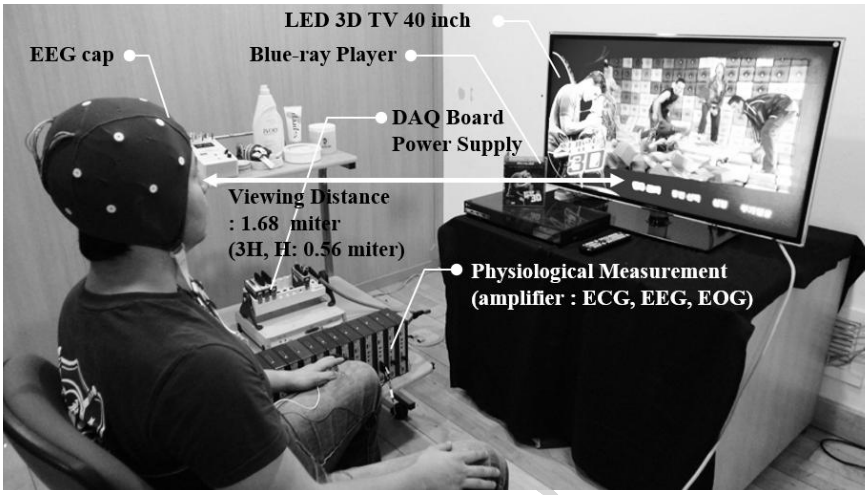

Fig. 3. Experimental setup

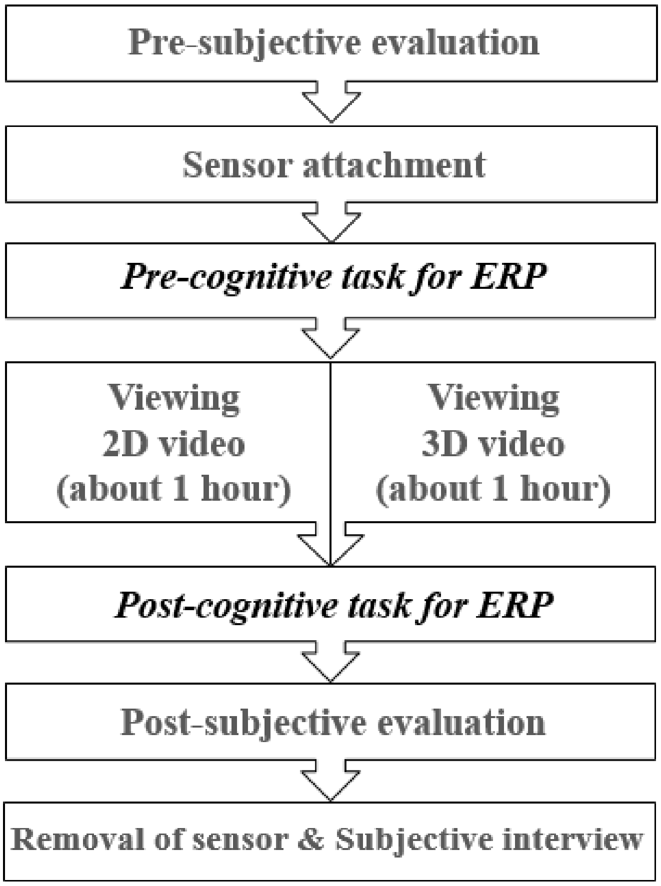

Fig. 4. Experimental procedure

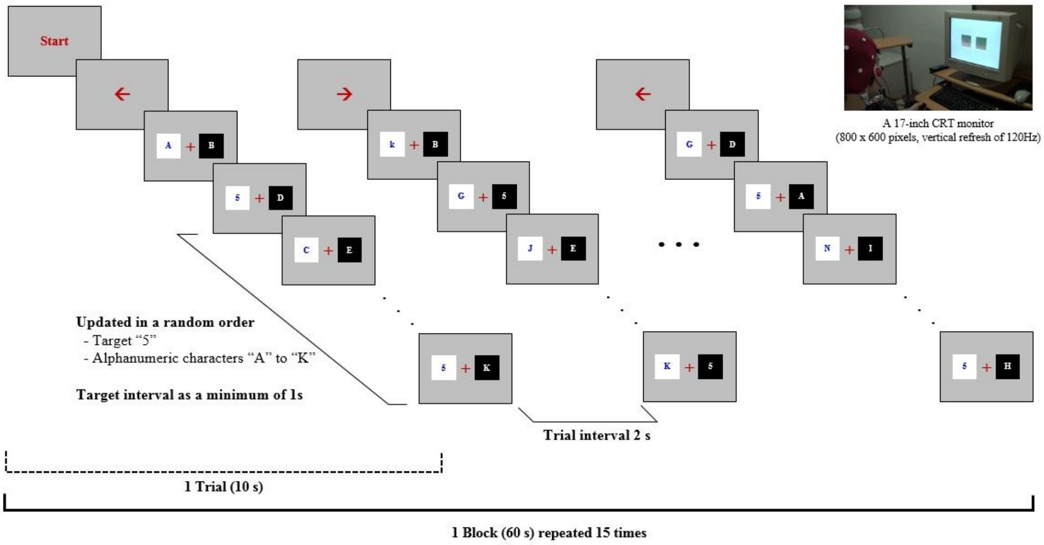

Fig. 5. Experimental stimuli and procedure for cognitive task

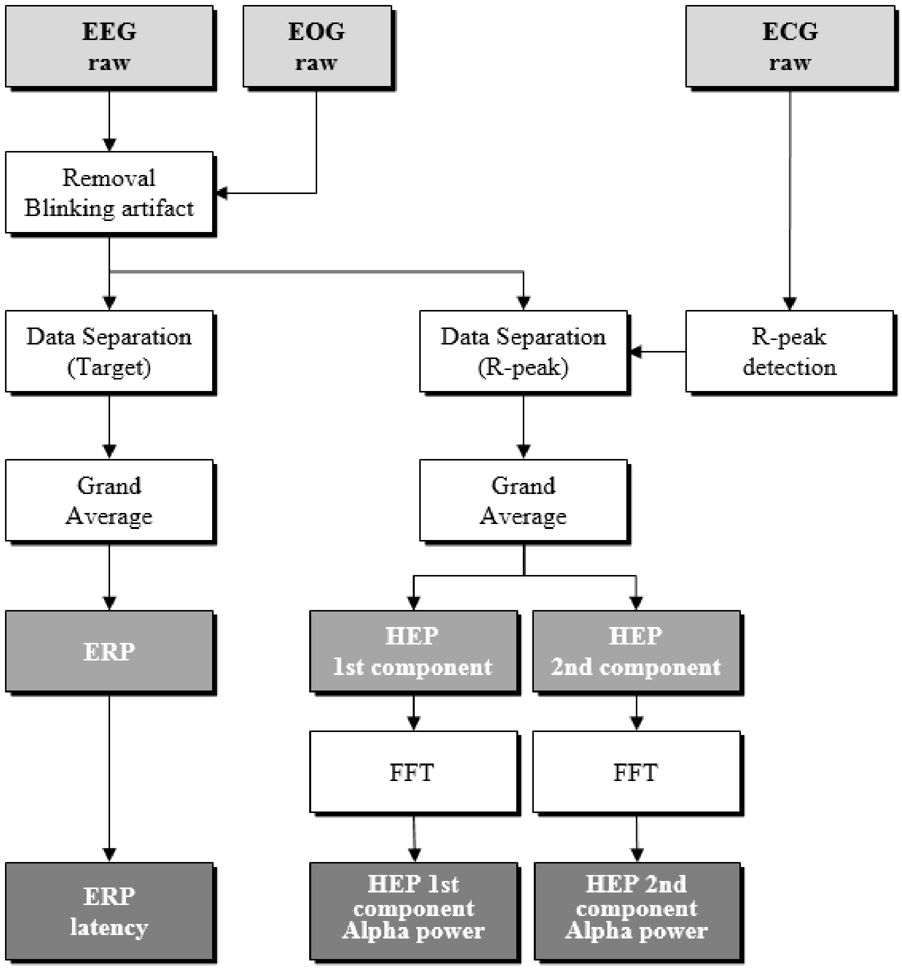

Fig. 6. Signal processing for analysis of ERP and HEP

Fig. 7. A frame correspondence of the used visual stimuli. (a) 2D version. (b) Left and Right image of 3D version of (a).

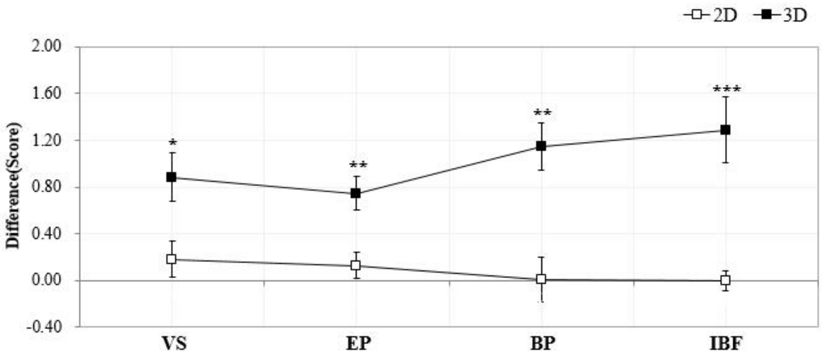

Fig. 8. Average subjective evaluation scores of four factors for 2D and 3D conditions. The subjective scale was evaluated a five-point scale about each four component (VS: Visual Stress; EP: Eye Pain; BP: Body Pain; IBF: Image blurring factor), and it was calculated the difference value between before and after each viewing condition (*, $p < 0.01$; **, $p < 0.0125$; ***, $p < 0.001$).

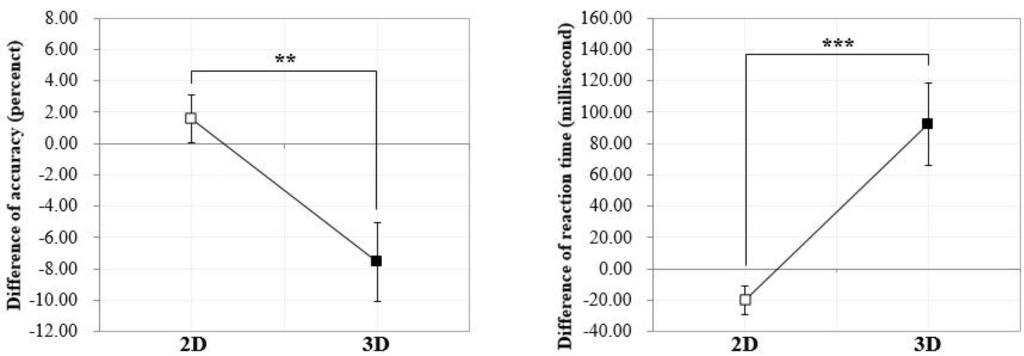

Fig. 9. Average accuracy (left) and reaction time (right) about presented target for 2D and 3D conditions. Both value were calculated the difference value between before and after each viewing condition (, $p < 0.005$; ***, $p < 0.001$).**

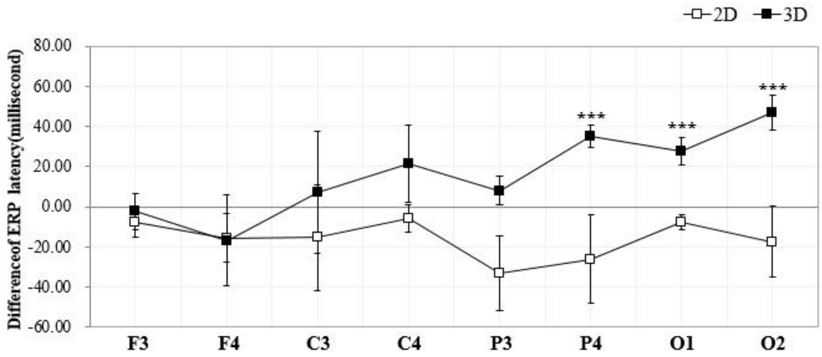

Fig. 10. Average ERP latency in eight brain regions for 2D and 3D conditions. The ERP latency values (P600) were calculated the difference value between before and after each viewing condition (*, *p* < 0.001).**

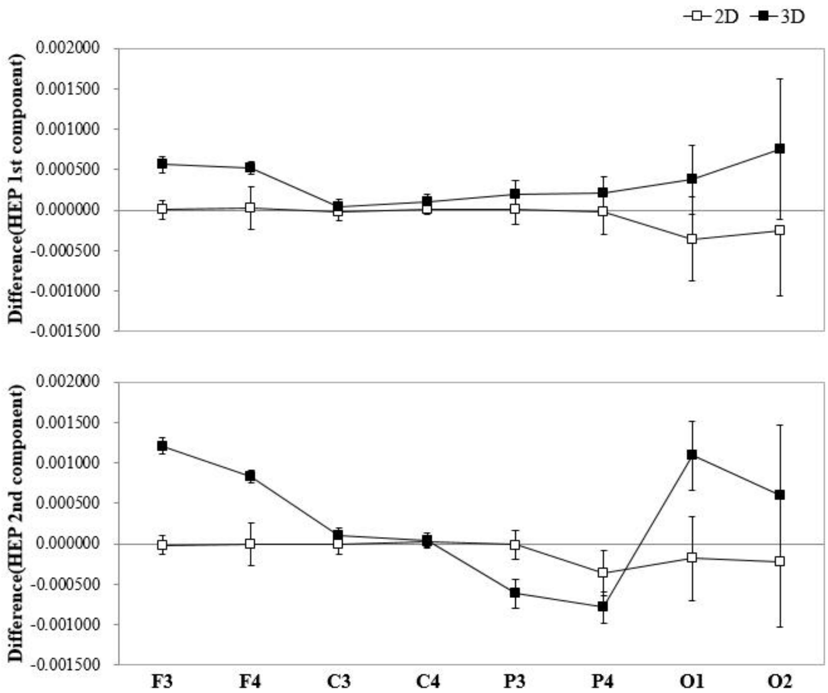

Fig. 11. Average value for the HEP first (alpha power in 50-250 ms period after the R-peak) and second (alpha power in 250-600 ms period after the R-peak) components in eight brain regions for 2D and 3D conditions. This values were calculated the difference value between before and after each viewing condition (, *p* < 0.003125)**

Table 1.Multitrait-multimethod correlation matrix. Correlation coefficients between subjective evaluation, performance, and electrophysiology measures (ERP and HEP) with 2D and 3D viewing condition

N = 30		2D Viewing Condition												3D Viewing Condition											
		SE_{EP}	SE_{BP}	SE_{IBP}	P_A	P_{RT}	$E(L)_{P4}$	$E(L)_{O1}$	$E(L)_{O2}$	$H(F)_{F3}$	$H(S)_{F3}$	$H(F)_{F4}$	$H(S)_{F4}$	SE_{EP}	SE_{BP}	SE_{IBP}	P_A	P_{RT}	$E(L)_{P4}$	$E(L)_{O1}$	$E(L)_{O2}$	$H(F)_{F3}$	$H(S)_{F3}$	$H(F)_{F4}$	$H(S)_{F4}$
2D-VC	SE_{EP}	.74																							
	SE_{BP}	.50	.72																						
	SE_{IBP}	.24	.44	.77																					
	P_A			.33	.66																				
	P_{RT}			.41	-.51	.68																			
	$E(L)_{P4}$		.23				.66																		
	$E(L)_{O1}$			.26			.48	.67																	
	$E(L)_{O2}$		.24				.47	.42	.66																
	$H(F)_{F3}$		-.35		-.25	.32	.47	.51	.44	.75															
	$H(S)_{F3}$				-.31	.36	.49	.60	.57	.63	.84														
	$H(F)_{F4}$					.21	.45	.48	.54	.62	.61	.76													
	$H(S)_{F4}$				-.28	.34	.41	.64	.61	.70	.62	.64	.89												
3D-VC	SE_{EP}	.48	.37	.46	-.39	.36							.44	.65											
	SE_{BP}	.26	.33	.21					.28			.26	.40	.42	.71										
	SE_{IBP}			.32	.26	.21	.20			.37	.36			.30	.35	.75									
	P_A	-.21	-.33	-.34	.32	.23	.21	.40	.33	.38				-.40		-.47	.48								

P_{RT}	.22	.42	.23		.37	.26				.22	.25	.31	.41	.31	.21	-.43	.54							
$E(L)_{P4}$		.35	.34			.46	.23						.20		.29	-.51	.34	.79						
$E(L)_{O1}$	.35		.33	.28		.28	.66	.32	.34	.30	.43	.33			.23	-.27	.36	.53	.75					
$E(L)_{O2}$	.26	.36	.31			.46	.46	.60				.33	.20		.24	-.31	.31	.43	.29	.72				
$H(F)_{F3}$	.27		.20			.32	.33	.42	.77	.34	.51	.47			.22	-.32	.39	.70	.94	.80	.82			
$H(S)_{F3}$	.33	.28	.31		.28	.28	.39	.25	.37	.71		.24			.31	-.23	.31	.50	.99	.62	.72	.92		
$H(F)_{F4}$	.31	.36	.28	-.34	.37	.34	.33	.43	.38	.41	.77				.31	-.32	.27	.64	.92	.73	.81	.83	.80	
$H(S)_{F4}$	.29	.33	.34	-.41	.40	.42	.42	.47	.41	.44	.43	.76			.34	-.32	.29	.51	.97	.61	.81	.87	.80	.94

Notes: The retest reliability (Cronbach's alpha) is shown main diagonal with black (monotrait-monomethod). Discriminant validity is shown the heterotrait-monomethod triangle with light grey. Convergent validity is shown the monotrait-heteromethod diagonal with dark grey. Correlation coefficients between other traits are not shown when smaller than .20 ($p > .01$). The abbreviation in the table followed that; SE_{EP}, SE_{BP}, and SE_{IBF}-subjective evaluation (eye pain, body pain, and image blurring factor); P_A and P_{RT}-performance (accuracy and reaction time); $E(L)_{P4}$, $E(L)_{O1}$, and $E(L)_{O2}$-ERP latency (P4, O1, and O2 brain region); $H(F)_{F3}$ and $H(F)_{F4}$-HEP first component (F3 and F4 brain region); $H(S)_{F3}$ and $H(S)_{F4}$-HEP second component (F3 and F4 brain region)

Highlights

3D viewing was significantly increased HEP (first & second components) at F3 and F4.

HEP measure showed high reliability and convergent validity rather than other measures.

HEP validated the usage of the measurement as indicator of cognitive function.

HEP was recommended as better evaluators of 3D visual fatigue than other measure.