Towards EEG-Based Haptic Interaction within Virtual Environments

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ABSTRACT

Current virtual environments (VE) enable perceiving haptic stimuli to facilitate 3D user interaction, but lack brain-interfacial contents. Using electroencephalography (EEG), we undertook a feasibility study on exploring event-related potential (ERP) patterns of the user's brain responses during haptic interaction within a VE. The interaction was flying a virtual drone along a curved transmission line to detect defects under the stimuli (e.g., force increase and/or vibrotactile cues). We found that there were variations in the peak amplitudes and latencies (as ERP patterns) of the responses at about 200 ms post the onset of the stimuli. The largest negative peak occurred during 200~400 ms after the onset in all vibration-related blocks. Moreover, the amplitudes and latencies of the peak were differentiable among the vibration-related blocks. These findings imply feasible decoding of the brain responses during haptic interaction within VEs.

Keywords: virtual reality (VR); haptic stimuli; force; vibration; electroencephalography (EEG); event-related potential (ERP).

Index Terms: H.1.2 [User/Machine Systems]: Human information processing; H.5.1 [Multimedia Information Systems]: Artificial, augmented, and virtual realities; H.5.2 [User Interfaces]: Haptic I/O

1 INTRODUCTION

Perception of haptic stimuli facilitates user interaction in a three-dimensional (3D) virtual environment (VE) [7]. Such haptic interaction could be more intuitive by enabling brain-interfacial contents [2, 8, 12]. The enabling requires to interface patterns (e.g., amplitude, timing, etc.) of the user's brain responses for the interaction. Thus, extracting such patterns is of importance.

Studies on haptic perception reported various patterns related to specific stimuli for different tasks [3, 7]. For example, the brain responses of perceiving vibrotactile cues (one haptic stimulus) were recorded using non-invasive electroencephalography (EEG) [11]. Most EEG recordings focused on user perception without considering 3D interaction. Exceptions were two studies undertaking 3D interaction within a VE but involving no haptic stimuli [4, 5]. The patterns of EEG related to stimuli are often examined using event-related potential (ERP) analysis [1, 2]. The ERP patterns are however underexplored for haptic interaction, which involves force and/or vibrotactile cues (two haptic stimuli) to evoke two different mechanoreceptors. Herein, we investigated preliminarily a feasibility of exploring ERP patterns of perceiving the stimuli during haptic interaction in a VE.

2 METHODS

Study Design: The feasibility study applied a 3D stereoscopic VE – developed with Unity 3D (5.3.2f1) – for a participant to perform an interactive task of flying a virtual drone along a curved transmission line [10]. Six male healthy volunteers (age of 23.8 ± 2.7 years old and naïve to the purpose of the study) participated in the study. As shown in Fig. 1(a), each participant used his right dominant hand to employ a haptic device (Omni; Geomagic, USA) for guiding the drone. The stylus of the device provided force cues to his right hand, while the first motor of a vibrotactile bracelet (VibroTac; Sensodrive Gmbh, Germany) offered vibrotactile cues either co-located with the stylus as depicted in Fig. 1(b) or dis-located with the stylus as illustrated in Fig. 1(a). The left wrist of the participant wore a wristband (E4; Empatica Inc., Italy) to monitor physiological signals for cybersickness. The participant's head donned a wireless cap (Enobio-20; Neuroelectrics, Spain) to record EEG data during his performing the task. Figure 1(c) indicates the placement of all 20 electrodes on the cap. The study had an ethics certificate from our institute.

During the task, each participant inspected the transmission line for defects using a robotic arm attached to the drone. A defect was signaled to the participant for 1000 ms as a force cue (100 mN force increase) and/or a vibrotactile cue (200 Hz vibration). The participant was instructed to declare a defect as soon as sensing the cue(s) by pressing down simultaneously the two buttons on the stylus. The participant undertook a training session, followed by a testing session. As depicted in Fig. 2, the testing session had 5 blocks corresponding to 5 combinations of the cues as: a sole force increase (F^+), a sole vibration on the right hand (V_co), a sole vibration on the right forearm (V_dis), the force increase and vibration co-located (FV_co), and the force and vibration dis-located (FV_dis). Each block had 15 defects located on the transmission line differently. The order of the blocks was counter-balanced among all participants. Each participant spent about 2 hours for both training and testing sessions.

Data Acquisition and Analyses: During the task, the VE logged behavioral data, such as physiological signals and the timing of defect detection. The logging was in synchronization with EEG recording. Each of 20 electrodes on the wireless cap recorded EEG data at 500 Hz, higher than the Nyquist sampling rate for the typical EEG Gamma-band frequency of 100 Hz. The reference electrode was placed near the right earlobe referring to Fig. 1(c).

Only data from the testing blocks were used for offline analyses. Against their baseline logged before the training session, physiological signals were checked for unusual changes. The timing of defect detections (i.e., correct responses) was examined from the onset (at 0 ms) of a defect to cover its entire activation [0,

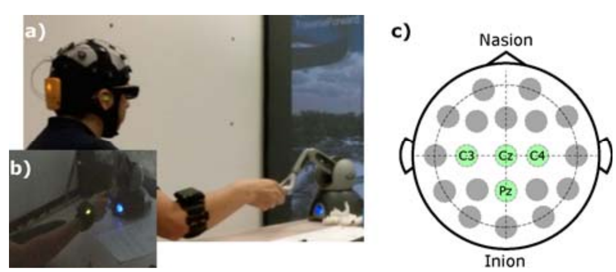

Figure 1: VE setup: (a) dis-located force and vibrotactile cues; (b) co-located same cues; and (c) placement of EEG electrodes.

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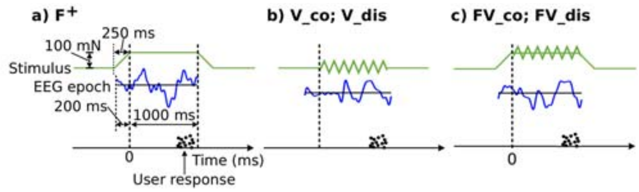

Figure 2: Haptic stimuli of all testing blocks: (a) F^+ (100 mN); (b) V_co and V_dis (200 Hz); (c) FV_co and FV_dis.

1000] ms. Button-pressing outside the activation was considered as incorrect responses and thus removed. Raw EEG data were band-pass filtered at 1-35Hz to eliminate commonly known artifacts [9]. The filtered data were then analyzed by applying custom MATLAB scripts utilizing EEGLAB v13.4 [10]. As depicted in Fig. 2, each analysis time-window (i.e., epoch) was extracted from the filtered data during an interval [-200, 1000] ms. That is, the interval began at 200 ms prior to the defect onset (at 0 ms) and lasted to cover the entire activation (1000 ms) of the cue(s). The baseline for an ERP analysis was taken from the data during [-200, 0] ms of each epoch. A threshold of 1000 μV was applied to reject artifact-contaminated epochs automatically. The remaining epochs with the correct responses were valid for analyzing both behavioral responses and ERP patterns. For these analyses, statistical significances among the testing blocks were evaluated by using one-way ANOVA along with Tukey's test for post-hoc assessments.

3 Results and Discussion

None of the participants had cybersickness by their physiological signals. Thus, all of their behavioral and EEG data were used in analyzing behavioral responses and ERP patterns.

Behavioral Responses: A total of 126 valid epochs were obtained across the 5 testing blocks among all participants. On average, the response times of the blocks were as: 727.3 ± 106.7 ms (F^+), 802.4 ± 64.5 ms (V_co), 824.0 ± 59.3 ms (V_dis), 822.0 ± 56.3 ms (FV_co), and 808.7 ± 67.5 ms (FV_dis). There were no significant differences of the response times among all blocks [$F(4, 125) = 1.40$, $p > 0.05$]. However, the F^+ block yielded a significantly lower percentage of the correct responses than other blocks for all participants [$F(4, 29) = 10.82$, $p < 0.001$]. All vibration-related blocks exhibited no difference among their percentages of the responses. The findings related to the percentage of the correct responses agreed with those in prior work [10].

ERP Patterns: For preliminary analyses, the F^+ block was excluded due to its insufficient number of valid epochs. The analyses used individual valid epochs of the Pz, Cz, C3, and C4 electrodes as depicted in Fig. 1(c). These electrodes overlay approximately the primary sensorimotor areas of the brain. An average N200 component – a negative peak occurred about 200~400 ms after the onset of the cue(s) [9] – was observed for the electrodes in all vibration-related blocks. Considering the peak and the timing (i.e., latency) of the peak with respect to the onset as ERP patterns of interest, the electrodes yielded similar ERP patterns for all participants to allow group analyses.

Table 1 summarizes the averaged ERP patterns of all participants over the electrodes. There were 76 valid peak amplitudes (A) and latencies (L) averaged over all participants. A decrease in the amplitudes was observed for the V_co and FV_co blocks, compared respectively to the V_dis and FV_dis blocks. The FV_co and FV_dis blocks had larger amplitudes than the V_co and V_dis blocks. ANOVA analyses of the amplitudes revealed a significant difference among the 4 blocks [$F(3, 75) = 5.54$; $p = 0.005$]. Post-hoc analyses indicated a significant increase in the amplitude of the FV_co block compared to both V_co and V_dis blocks. That is, the co-located force increase and vibration elicited larger amplitudes. This agrees with evidence of effective information processing [6].

Table 1: Tukey's test for peak amplitude and latency*

	V_co	V_dis	FV_co	FV_dis	A (μV)**
	-5.14 ± 3.88	-3.12 ± 4.84	-10.2 ± 5.28	-6.54 ± 6.49	μ ± SD†
V_co		$p = 0.63$	$\mathbf{p = 0.029}$	$p = 0.85$	V_co
V_dis	$p = 0.075$		$\mathbf{p = 0.0001}$	$p = 0.20$	V_dis
FV_co	$\mathbf{p = 0.017}$	$p = 0.89$		$p = 0.18$	FV_co
FV_dis	$\mathbf{p = 0.045}$	$p = 0.99$	$p = 0.95$		FV_dis
μ ± SD†	227.3 ± 33.2	198.3 ± 30.7	189.3 ± 24.9	195.8 ± 49.5	
L(ms)‡	V_co	V_dis	FV_co	FV_dis	

[NOTES: * bolded *p* indicating significant differences; ** peak amplitude; †mean ± standard deviation; ‡ peak latency; A: amplitude; L: latency.]

ANOVA analyses on the latencies showed a significant decrease among the 4 blocks [$F(3, 75) = 3.92$; $p < 0.05$]. Post-hoc analyses indicated the decrease derived from the lower latencies of the FV_co and FV_dis blocks, compared to the V_co block. On average, the FV_co and FV_dis blocks yielded a latency reduction compared to both V_co and V_dis blocks. This latency reduction, along with the amplitude increase, for the cue-combined blocks might reflect less needs of attention resources for perceiving combined stimuli than an individual stimulus for haptic interaction.

The above findings implied a feasible differentiation of ERP patterns between vibrotactile cues and their combinations with the force increase, even though such differentiation was unapparent behaviorally. The findings were based on a small number of the participants and explored EEG data of limited electrodes. For potential EEG-based haptic interaction in VEs, more studies are necessary to identify brain responses and to reinforce the findings.

4 Conclusion

This preliminary study explored feasibly ERP patterns during haptic interaction in a VE. Future work is needed to identify these patterns for potential EEG-based haptic interaction.

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