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Analysis of Physiological Response to Two Virtual Environments: Driving and Flying Simulation

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ABSTRACT

As virtual reality technology continues to attract significant attention in clinical psychology, especially in the treatment of phobias, physiological monitoring is increasingly considered as an objective measurement tool for studying participants. There are few studies, however, of the normal physiological response to virtual environments or reactions to different virtual environments. The goal of this study is to analyze nonphobic participants' physiological reactions to two virtual environments: driving and flying. Eleven nonphobic participants were exposed to each virtual environment for 15 min. Heart rate, skin resistance, and skin temperature were measured during physiological monitoring, and the Presence and Simulator Sickness Questionnaire scores were obtained after each exposure. This study found that skin resistance and heart rate variability can be used to show arousal of participants exposed to the virtual environment experience and that such measures generally returned to normal over time. The data suggest that skin resistance and heart rate can be used as objective measures in monitoring the reaction of non-phobic participants to virtual environments. We also noted that heart rate variability could be useful for assessing the emotional states of participants.

INTRODUCTION

Virtual reality (VR) has been attracting increasing attention in clinical psychology, especially in the treatment of phobias.[1–5] At the same time, physiological monitoring has become important as an objective measuring tool for evaluating the emotional state of participants.[6–9] Also, real-time physiological monitoring has been used as an indicator of excessive patient arousal and the need to be placed back at a lower level of the fear hierarchy or removed from the phobic scenario altogether during the therapy session.[22] Conversely, knowledge about the physiological consequences for users of virtual environments (VEs) is limited. Meehan stated that heart rate had a high and significant correlation with presence in VEs and could be used as an objective measurement of presence.[9] Also Wiederhold has demonstrated the differences between nonphobic's physiological responses and phobic's responses when placed in VEs.[10] Although the number of participants was small, this study revealed that physiological measures were related to presence, degree of realism, and immersiveness. Regenbrecht described a 37-subject study in which the relationship between presence and fear of heights was analyzed.[11] The analysis showed that

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reported fear had a significant relationship with height anxiety (positive), height avoidance (negative), and presence (positive). That is, reported fear was significantly higher for subjects who reported higher presence and (preexperiment) height anxiety. In the current study, nonphobic participants' physiological reactions to VEs were analyzed, and their physiological characteristics and trends were investigated in two VEs: driving and flying.

MATERIALS AND METHODS

Subjects

Eleven volunteers (24.9 ± 5.82) over 18 years of age were chosen as nonphobic participants for this study. A participant was excluded from the study if he or she had a history of heart disease, migraines, seizures, or a concurrent diagnosis of severe mental disorders such as psychosis or major depressive disorder as determined by an intake interview and evaluation.

Virtual environments

Two VEs were used in this study. The first environment, a flying simulator for fear of flying, had one interaction interface: a head motion tracking device. The second VE for fear of driving had two interaction interface with the participant: a head motion tracking device and a driving control device. Therefore, the driving simulator was considered to be more interactive than the flying simulator.

*Virtual environment for fear of flying.*The VE for this study consisted of a head-mounted display (HMD; VFX3D), a head tracker, and a flight seat with a subwoofer that produced vibrations. It was designed by Drs. Hodges and Rothbaum of Virtually Better, Inc. (Atlanta, GA), who have previously performed VR treatment for acrophobia and fear of flying.[1,12] It places the participant in a window seat of the passenger cabin of a commercial airplane. The therapist can expose the patient to different aspects of a complete flying experience such as sitting in the plane with the engines on or off, taxiing on the runway, takeoff, flying in either smooth or turbulent weather, as well as landing (Fig. 1).

Virtual environment for fear of driving. Our group also developed a VE for fear of driving. It consisted of an HMD (VFX3D), a three-degree-of-freedom head motion tracker, a steering wheel (Wingman Formula GT), and a vibration chair using sound produced by the computer. The driving software was developed on a Pentium 600 personal computer with a three-dimensional (3D) accelerator graphics card. It largely consisted of three parts: an urban street, a secluded road, and a tunnel. The participant began to drive on a two-lane urban street and drove to the secluded road without buildings or people. There also was a long tunnel with a traffic jam. The participant could be detained inside the tunnel, and the operator was able to control the traffic. The traffic lights and sounds mimicked those found in real world (Fig. 2).

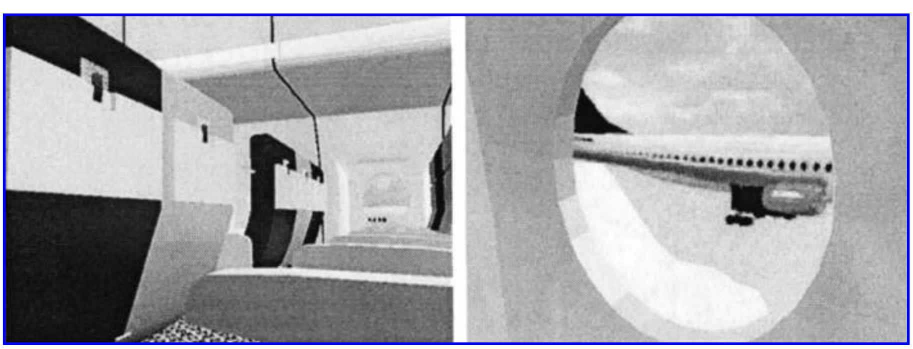

FIG. 1. Scenes from the VE flying simulator.

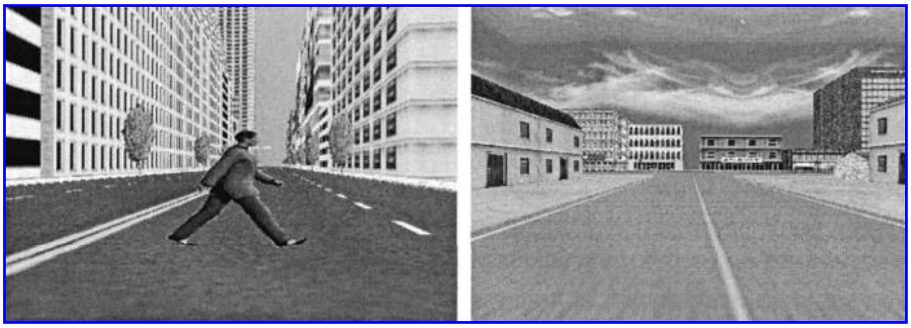

FIG. 2. Scenes from the VE driving simulator.

Measures

Physiology. Skin resistance (SR) was measured to observe the changes in sweat gland activity. SR generally decreases as sweat gland activity increases. SR was monitored with two silver/silver chloride electrodes placed on the ring and index fingers of the left hand. For heart rate (HR), a small amount of electrode gel was placed on each of two disposable electrodes attached to the participants' right and left wrists. The temperature sensor was placed the ring finger on the right hand with adhesive tape for measuring skin temperature. An I-330 C-2 computerized biofeedback system manufactured by J&J Engineering (Poulsbo, WA) was used to collect physiological data.

Questionnaires. The Simulator Sickness Questionnaire (SSQ) provided measurements of simulator sickness.[13] The SSQ is a 16-item symptom checklist. The Presence & Realism Questionnaire (PRQ) rated the sense of presence and degree of realism felt in the virtual environment.[14] The PRQ consists of a 10-item presence and realism checklist as well as, overall rate of realism, and an overall rate of presence. The Tellegen Absorption Scale (TAS) assessed the participant's ability to become deeply absorbed into what they were doing or in their environment.[15] The Dissociative Experiences Scale (DES) measured the capacity for dissociation.[16] It consists of 28 questions about experiences that one may have in daily life.

Virtual reality exposure procedure

After signing an informed consent, the participant was asked to fill out the two questionnaires: DES and TAS. To begin with, a flying simulation of two VEs was experienced. A 5-min eyes-open baseline then was taken in order to objectively analyze physiological response in the virtual environment. The participant was placed in a VFX3D HMD. The participant was allowed to look around the virtual plane to become oriented for a short while before the flight began. The participant wore a HMD and viewed a 3D computer-generated image of the following flying scenes: sitting in the passenger cabin of a plane with the engines on, taxiing, taking off, flying in good weather, flying in bad weather, and landing. The participant took a rest for 60 min after finishing the VR flying experience to remove any interference or influences of the experience with subsequent exposures (i.e., the VR driving simulation). After a 5-min eyes-open baseline was taken, the participant was instructed to follow the traffic and directional signs, which showed how to proceed. They were shown how to control the wheel with their right hand to minimize the movement noise in obtaining physiological data. During the 15-min driving experience wearing a HMD, the participant felt the vibration of the chair through the subwoofer.

Analysis

Baseline levels vary widely by individual or environment so percentage change from baseline was measured rather than absolute value. Therefore, before comparing physiology with presence measures, percentage change of skin resistance (ΔSR) and temperature (ΔST) was calculated as follows:

$$\Delta X = (MeanVR - MeanBaseline)/MeanBaseline$$

where ΔX is defined as the percentage of physiological measure, MeanVR is defined as the average of physiological measure during experiencing VR, and MeanBaseline is defined as the average of physiological measure during baseline.

The percentage change of skin temperature (ΔST) and the percentage change of skin resistance (ΔSR) were calculated using the same method. Also, for assessing the autonomic balance in VEs, heart rate variability analysis was used. Heart rate variability measures the interval of time between each individual heartbeat and usually is calculated based on the R-R interval from the EKG.

RESULTS

Table 1 shows the result of a conventional Student *t* test of physiological responses and questionnaires between flying VEs and the driving VEs. Although the skin resistances in the two VEs did not show significant differences ($p = 0.081$) because of the small number sample size, the change of SR over time presented very different reactions according to the particular VEs (Fig. 3). The study showed that the participants were initially aroused in the VE exposure, but returned to normal after approximately 7 min in each of the two VEs. The driving VE, however, required the participant's attention and alertness more than the flying VE, since the participants had to pay more attention to control the steering wheel. After habituation for 7 min, therefore, overall SR reaction in the driving VE was more active than for the flying VE. This was matched with Slator's study, which showed that individuals feel presence in active VEs, which react to their movements or actions more than passive VEs.[17] Contrary to the results of the physiological response, however, there was no significant differences in the scores of the Presence Questionnaire.

The analysis of age and SSQ by Pearson correlation showed that there was a significant correlation ($r = 0.902$, $p = 0.0001$) between age and SSQ after the driving VE, while there was no correlation ($r = 0.390$, $p = 0.914$) between age and SSQ after the flying VE. It appears that the older participants felt sickness in the complex VEs more than the younger participants. The driving VE had two control devices: a head motion tracker and a steering wheel, and the view changes by those devices evoked sickness in the older participants.

In the analysis of heart rate variability, there were no significant differences between baseline and VE exposure except heart rates ($p = 0.004$) in the driving VE (Table 2). However, the trend of the LF/HF ratio demonstrated a similar pattern to the SR response (Fig. 2). This ratio is used for estimating the overall balance between the sympathetic and parasympathetic systems. A higher number indicates increased sympathetic activity or reduced parasympathetic activity. Therefore, Figure 4 shows that participants aroused at the beginning of expo-

TABLE 1. THE STUDENT *T*-TEST OF TWO VIRTUAL ENVIRONMENTS (FLYING AND DRIVING SIMULATORS) IN SKIN TEMPERATURE, SKIN RESISTANCE, SIMULATOR SICKNESS QUESTIONNAIRE, AND PRESENCE QUESTIONNAIRE

Measures	*VE*	*Statistics*	*Student* t *test*	p
∇Skin temperature	Flying	0.016 ± 0.059	1.138	0.282
	Driving	0.0013 ± 0.033		
∇Skin resistance	Flying	0.198 ± 0.292	1.938	0.081
	Driving	-0.103 ± 0.486		
Simulator sickness questionnaire	Flying	2.9 ± 1.66	1.892	0.091
	Driving	11.2 ± 13.6		
Presence	Flying	11.6 ± 5.10	0.577	0.578
	Driving	10.7 ± 7.04		

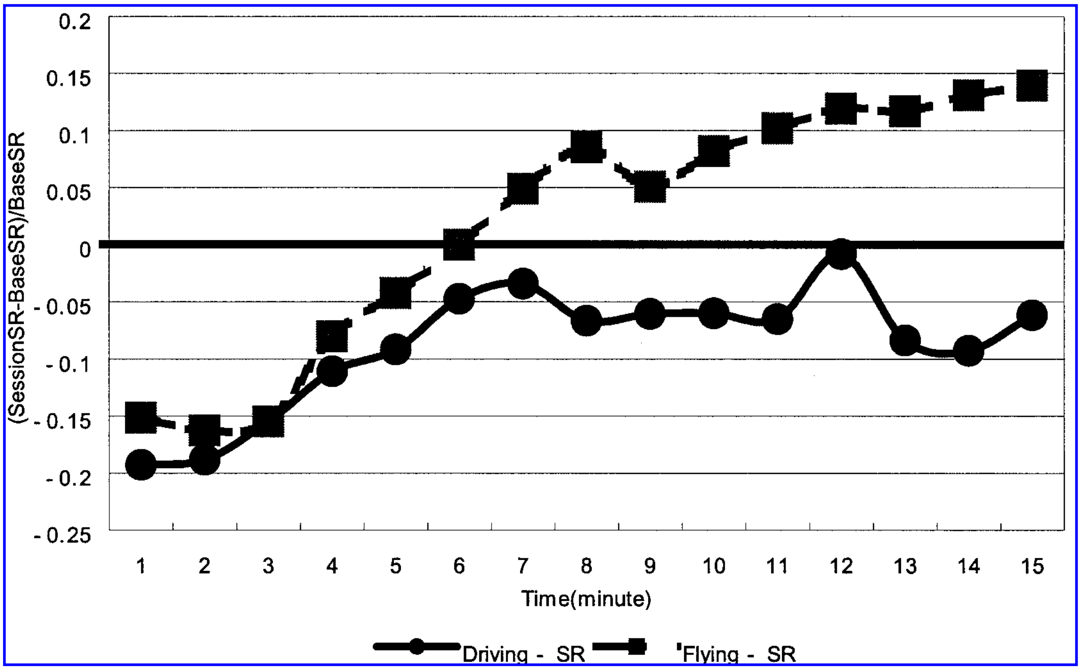

FIG. 3. The change of skin resistance over time. Values were the average of all of the participant's skin resistance change rates: (SessionSR − BaseSR)/BaseSR. The figure showed that the participants were aroused initially in VE exposure and returned to the normal after approximately 7 min.

sure are habituated after approximately 8 min, in that the LF/HF ratio returns to the baseline. Figure 5 presented an example of the most typical responses. After exposure to VEs, there was an increase in heart rate fluctuation (Fig. 5a), which is reflected in the increase of low-frequency power and a decrease of high-frequency power (Fig. 5c).

TAS and DES did not show any correlation with the other questionnaires and physiological measures probably due to the small number of cases.

TABLE 2. CHANGE IN HEART RATE, LOW-FREQUENCY POWER (LF), HIGH-FREQUENCY POWER (HF), NORMALIZATION OF LF, NORMALIZATION OF HF, AND THE RATIO OF LF/HF IN BASELINE BEFORE EXPOSURE TO VR AND DURING EXPOSURE TO VR

	Parameter	*Baseline*	*Exposure to VR*	
Flying virtual environment	Heart rate (beats/min)	68.8 ± 8.15	69.1 ± 7.92	0.505
	Low-frequency power	362 ± 121	519 ± 274	0.101
	High-frequency power	274 ± 114	279 ± 107	0.905
	LF normalization	49.3 ± 10.8	55.4 ± 12.7	0.359
	HF normalization	36.3 ± 10.5	32.4 ± 11.0	0.520
	LFP/HFP	1.49 ± 0.57	2.02 ± 1.21	0.319
Driving virtual environment	Heart rate (beats/min)	71.1 ± 6.06	73.6 ± 5.64	0.004
	Low-frequency power	378 ± 239	390 ± 286	0.762
	High-frequency power	251 ± 114	205 ± 136	0.246
	LF normalization	52.5 ± 11.0	39.3 ± 14.8	0.147
	HF normalization	35.6 ± 12.0	32.3 ± 14.1	0.486
	LFP/HFP	1.71 ± 0.88	2.38 ± 1.52	0.189

Values are listed as mean ± one SD.
VR, virtual reality.

FIG. 4. The time-plot of the LF/HF ratio was obtained by the average of the flying VE participants' LF/HF ratios. The ratio value was calculated with the previous 5 min by that time.

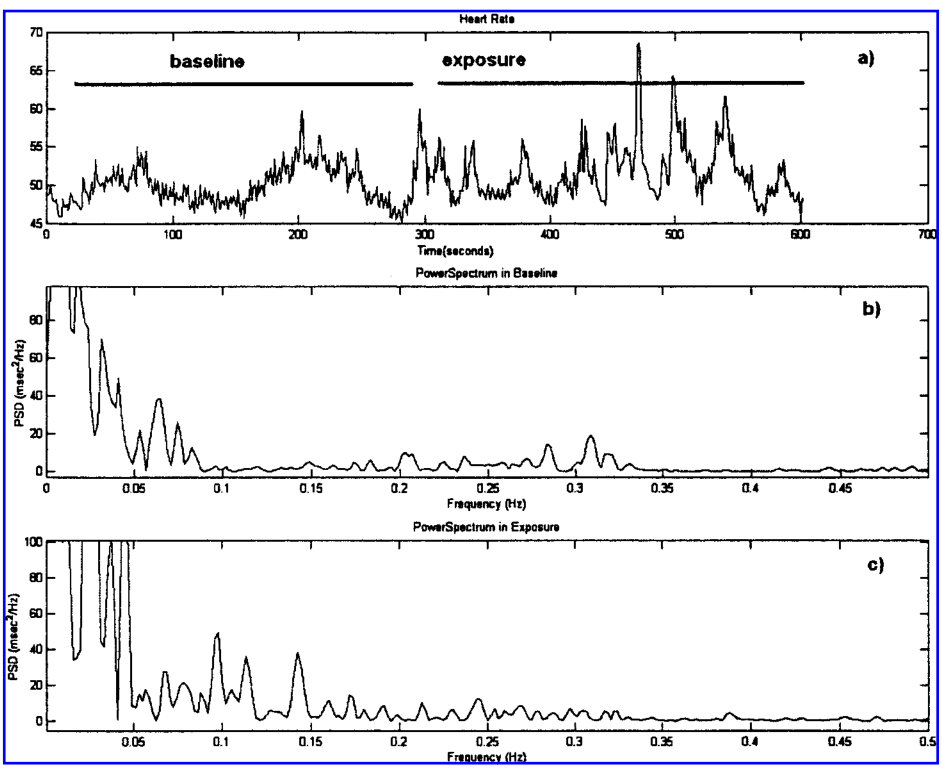

FIG. 5. (**a**) Time series (600 sec) of heart rate in baseline and in the exposure to VEs. (**b**) The power spectral density curve of heart rate time series in baseline. (**c**) The same density curve in exposure to VEs.

DISCUSSION

When placed in a VE, a new and novel stimulus, SR levels decreased, indicating some physiological arousal. Early in the last century, Carl Jung reported: "Every stimulus accompanied by an emotion produced a deviation of the galvanometer to a degree in direct proportion to the liveliness and actuality of the emotion aroused".[18] We also found that SR increases over time after approximately 7–8 min, supporting the idea that subjects could become habituated to VEs. The result showed again that SR could be used as an objective measurement for checking the state of participants in the field of VR psychotherapy. However, it was not found that heart rate decreased over time, as reported by Meehan.[19]

There was an interesting trend in SR over time within the two VEs of driving and flying. While there was no significant difference in the presence questionnaires, the trend of skin resistances has a different pattern in Figure 2 and Table 1. It was expected that active VEs (such as the driving VE) would evoke higher presence and physiological arousal than passive VEs (such as the flying VE). Paying more attention in order to control the steering wheel might explain the physiological responses seen, which may have superseded the presence effect.

Heart rate variability (HRV) has been generally used for the recognition of autonomic activity in various fields.[20] Although the HRV analysis in this experiment did not show significant differences between the two VEs, small sample size was probably the major factor. An analysis of HRV frequency ratios, however, did indicate some interesting preliminary results. One was that the LF/HF ratio in exposure to VEs was higher than that in baseline. The LF/HF ratio refers to the ratio of the low-frequency component and the high-frequency component in the power spectrum density of heart rates. As previously mentioned, this is generally believed to indicate sympathetic balance. The higher value of the LF/HF ratio reflects the change of that balance, that is, the response to a new and novel stimulus such as a VE.

Further, the trend of the LF/HF ratio showed almost the same pattern as the SR response. This supports the usability of LF/HF ratios as an objective measure for monitoring a participant's reaction to VEs. HRV analysis may also be considered important as a physiological response measure during psychotherapy using VR techniques. There is some evidence that stress management techniques improve the sympathetic–parasympathetic balance. Further analysis of physiological data may continue to provide useful information in understanding the response of humans to VEs.[21]

CONCLUSION

In this study, the physiological responses to two VEs were analyzed. It showed that SR and heart rate could be used as objective measures in monitoring reactions to VEs. HRV analysis in VEs may be useful for assessing the emotional states of participants in VEs.

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