

Heart-Rate Variability and Event-Related ECG in Virtual Environments

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Abstract

Beside standard questionnaires physiological measures can be used to describe the state of Presence in a virtual environment.

A total of 21 participants explored a virtual bar in a CAVE like system. The experiment was divided into a baseline-, training- and experimental phase. During the experimental phase breaks in presence (BIPS) in form of whiteouts of the virtual environment scenario were induced. The heart rate variability and the event-related ECG were calculated from the acquired ECG data. The study showed that the heart rate variability can be used as parameter that reflects the physiological state of the participant. The event-related ECG showed the effect of the induced BIPS and of speaking avatars on the subjects.

Keywords: break in presence, Virtual Reality, parasympathetic system, sympathetic system

1. Introduction

An important aspect of a virtual environment is to induce a state of Presence. Presence may be thought of as the observer's subjective sensation of "being there" in the virtual environment [3], although there are many other definitions, but this is not the point of this paper.

A strategy for measurement of presence was proposed by Slater and Steed [7]. This work is premised on the idea of eliciting moments in time when 'breaks in presence' (BIPs) occur. A BIP is any perceived phenomenon during the virtual environment (VE) exposure that launches the participant into awareness of the real-world setting of the experience, and therefore breaks their presence in the VE. Examples include gross events such as bumping into a 'Cave' wall, getting wrapped in cables, through to more subtle effects such as revelations that come from seeing a tree as a texture map rather than a solid object.

The measurement of presence can be done e.g. with subjective measures such as questionnaires and objective measures. Objective measures include the monitoring of the Electrocardiogram (ECG), respiration, galvanic skin response (GSR) and also the Electroencephalogram (EEG).

Galvanic skin response was used successfully to describe the relation between physiological response and virtual height exposure [5]. In the same study consistent changes in heart-rate and skin temperature were not observed. Changes in GSR signal were also useful to describe the anxiety during a virtual flight [11], whereas heart-rate, respiration and peripheral skin temperature did not show a correlation with the anxiety level.

Changes in heart-rate and GSR signal had also a high level of correlation with Presence questionnaire scores and indicated the degree of presence [12].

Recently, it was been shown that there is a very likely correlation in heart-rate and GSR changes associated with reporting of a BIP [8].

However, beside the GSR changes other parameters extracted from physiological signals can be used to describe subject specific reactions to the experimental setup. Especially from the ECG different parameters can be extracted. Beside the HR, the heart-rate variability (HRV) can be used to describe the physiological behavior of the participant. The event-related heart rate response is useful to describe the reaction of the subject to an event (e.g. BIP).

The variability of HR is also influenced by the autonomous nervous system (ANS) activity. Statistical measures in time and frequency domains are used for the quantification of the HRV. Recent studies show that the parasympathetic and sympathetic nervous activities influence the HRV at different frequencies [10].

In general there are several effects that change the HRV:

1. respiratory sinus arrhythmia (RSA) mediated by respiration. This activity is responsible for changes of the heart-rate in 2-5 seconds

intervals and is controlled by parasympathetic activity. The sympathetic system is too slow to influence this frequency band;

2. the blood pressure regulation contributes to HRV in 10 second rhythms;
3. changes with a periodic length above 20 seconds are mediated by the sympathetic system;
4. changes in the minutes and hours range are influenced by the neurohumoral oscillations in the circulating blood, by circadian rhythms or rapid eye movement phases during sleep

Hence different methods able to delineate the different influences of the ANS are therefore necessary.

Low levels of sympathetic activity result in slow oscillations of sympathetic activity entrained to the vasomotor oscillations. However, as the level of sympathetic activity increases, these oscillations are damped and the fluctuations disappear. Under intense sympathetic drive, the heart-rate becomes metronomic in its regularity. The coupling between sinus node oscillation and sympathetic oscillations drops down to zero [1, 4].

The parasympathetic system also influences the sinus node. Respiratory oscillations affect both the sympathetic and parasympathetic nervous system. However, because of the slow response time of the sympathetic system, these rapid oscillations are mediated purely by the parasympathetic system. The parasympathetic oscillations have typically the same frequency as the respiration frequency.

It is generally assumed that high HRV correlates with good health and low HRV with cardiovascular disease. Other reasons for a decrease in HRV are mental stress, depression and exercise. Low frequency components (LF, 0.1 Hz) and high frequency components (HF, 0.15-0.4 Hz) indicate mental stress when the LF component is increased and the HF component is decreased. During dynamic exercise the heart rate changes but the HF component does not change significantly.

2. Experiment

A total of 21 subjects explored a virtual bar in the breaks in presence (BIPs) experiment conducted in a four-walled Cave-like system. This is an approximately 3 meter cubed area, with projection screens on the floor and three walls (but not the ceiling). Each experimental session was divided into three phases:

1. a **baseline** phase during which subjects were standing in the Cave with no images displayed;
2. a **training** phase during which subjects were given a simple navigation task to help them feeling comfortable moving around the VE;
3. an **experiment** phase during which the subjects were in the virtual bar.

During the experiment phase a scenario of a 'bar' was displayed to the subjects. There were 5 virtual characters in the bar, a barman and two couples, one pair standing near the bar, and the others sitting across the room. These virtual characters (2 women and 2 men) would be 'aware' of the location of the participant and would often address remarks towards him/her. During the experience two songs played in the background one after the other, and in addition there was background chatter as might be heard in a real bar. The entire experience lasted approximately 5 minutes. The system was implemented using DIVE [2] and the network interface between the various components achieved using VRPN. The experiment was approved by the Ethics Committee.

During the experimental phase avatars were speaking to the subjects and artificial breaks in presence (BIPs) occurred. About 30 sentences were uttered by the virtual characters, and BIPs were induced four times by creating a visual "whiteout" in the Cave. These 'whiteouts' lasted for 2 seconds each, distributed approximately uniformly in time throughout the bar experience.

3. Methods

The ECG was acquired as standard Einthoven I derivation (sampling frequency: 256 Hz) and the analysis was performed with the g.BSanalyze biosignal analysis software package (g.tec – Guger Technologies OEG, Graz, Austria).

The first step in ECG analysis is to detect QRS (ventricular contraction) complexes in the ECG time series. The QRS complexes determine the distance in time from one heart contraction to the next one (RR interval). The term "NN interval" is used in the literature to indicate that only normal-to-normal beat distances are used for the calculations (non-normal beats like extra systoles are excluded). The QRS complexes in the ECG data were detected automatically based on a modified Pan-Tompkins algorithm [6]. Then a visual inspection of the detected QRS complexes was performed to guarantee high data quality.

Heart-rate variability

Changes in RR-intervals are referred to as HRV and can be described in time and frequency domains.

The following are most important time domain measures:

MeanRR - mean RR interval [ms]

SDNN - standard deviation of NN intervals [ms]

MaxRR - maximum RR interval [ms]

MinRR - minimum RR interval [ms]

MinMaxRR - difference between MaxRR and MinRR [ms]

MeanHR - mean heart rate [bpm]

SDHR - standard deviation of the heart-rate [bpm]

The segmented measures divide the recorded ECG signal into equally long segments to calculate:

SDANN - standard deviation of the average NN interval calculated over short periods

SDNNindex - mean of e.g. 1 min standard deviation of NN intervals calculated over total recording length

The following measures yield differences between adjacent intervals:

SDSD - standard deviation of successive NN differences [ms]

RMSSD - square root of the mean squared difference of successive NN intervals [ms]

NN50 - number of intervals of successive NN intervals greater than 50 ms

PNN50 - NN50 divided by the total number of NN intervals

Frequency domain measures provide information on how power is distributed as a function of frequency. RR time series were resampled with a frequency of 2 Hz. Then the power spectrum of the resampled time series were estimated with the Burg method [9] of order 15. The RR sequence was detrended and a Hanning window was applied prior to the spectrum estimation. The FFT length was 128 with an overlap of 64 and a sampling frequency of 2 Hz. Three main spectral components were distinguished: (i) very low frequency (VLF): <0.04 Hz, (ii) low frequency (LF): 0.04 – 0.15 Hz and (iii)

high frequency (HF): 0.15 – 0.4 Hz. The unit of these parameters is ms^2 . To express LF and HF in normalized units, each parameter is divided by the total power minus the VLF component. This minimizes the effect of the total power on LF and HF. The LF/HF ratio describes the balanced behavior of both components.

Event-related ECG (ER-ECG)

A specific number of RR intervals before the event and after the event (BIP, avatar speaking) were averaged. The difference shows the event-related change in HR. This procedure was repeated for all speaking events and separately for all BIPS. An important parameter is the number of RR intervals (n) used for the averaging. Therefore, the ER-ECG was calculated for n=2 up to n=30.

4. Results

Table 1 shows the changes of HRV parameters in time domain for the two phases: (i) **training** and (ii) **experimental** phase. A sign test for paired samples was applied between the parameters of the training and experimental phase. The 4th column gives the corresponding p-values. If the p-value is not given then the changes were not significant.

The analysis shows that there is a significant difference between the training and experimental phase in terms of the heart-rate (MeanHR): 93.41 bpm versus 88.33 bpm ($p=0.0072$) and also in the heart rate variability (HRV) parameters. RMSSD, SDSD, PNN50 and the SDNNindex are smaller in the training phase than in the experimental phase.

Table 1: HRV time domain parameters

| HRV | Training | Experimental | p value |
|-------------------|----------|--------------|---------|
| MeanRR [ms] | 654.71 | 693.53 | 0.0072 |
| SDNN [ms] | 42.39 | 41.62 | |
| MaxRR [ms] | 775.95 | 807.47 | |
| MinRR [ms] | 573.47 | 606.02 | 0.0266 |
| MinMaxRRDiff [ms] | 202.48 | 201.45 | |
| MeanHR [bpm] | 93.41 | 88.33 | 0.0072 |
| SDHR [bpm] | 5.84 | 5.22 | |
| RMSSD [ms] | 22.51 | 27.08 | 0.0266 |
| SDSD [ms] | 22.61 | 27.21 | 0.0266 |
| NN50 [nr] | 5.42 | 8.33 | |
| PNN50 [%] | 4.94 | 8.26 | 0.0118 |
| HRVindex [nr] | 8.57 | 8.90 | |
| SDANN [ms] | 16.92 | 16.69 | |
| SDNNindex [ms] | 37.46 | 40.86 | 0.0266 |

Figures 1 and 2 show the HRV frequency analysis results for one subject. During the training phase the LF component is increased to about 180 ms^2 and the HF component is decreased to about 5 ms^2 . In the experimental phase LF is about 118 ms^2 and HF is 18 ms^2 .

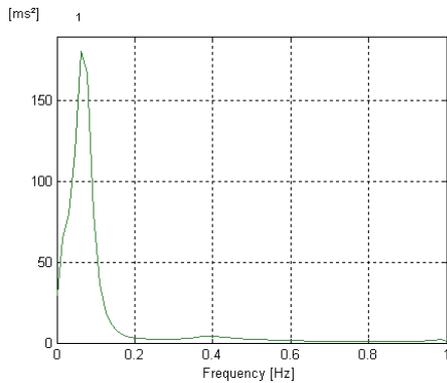


Figure 1: HRV in frequency domain of the training phase (subject 11)

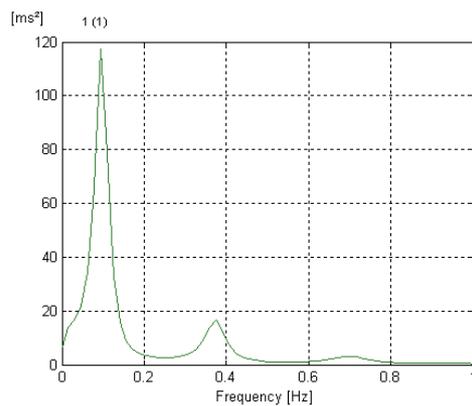


Figure 2: HRV in frequency domain of the experimental phase (subject 11)

The mean values for all subjects are represented in Table 2. Between training and experimental phase the normalized LF component (LFnorm) decreases from 74,5 to 64,9, the normalized HF component (HFnorm) increases from 15.1 to 22.3 and the LF/HF ratio decreases from 6.9 to 4.0. All three parameters have a p-value of 0.0266.

Figure 3 is a time frequency map of the HRV data. The map shows the evolution of the power spectrum over time for the baseline, training and experimental phase. An activated parasympathetic system yields frequency components in the HRV map around 0.35 Hz (HF component) and the sympathetic system yields frequency components around 0.1 Hz (LF component). Basically the LF component is dominant throughout the whole experiment. The HF component in contrast varies between the baseline-, training- and experimental phase. The arrows indicate the changes between the different experimental phases. It can be seen that the activated HF component from the baseline phase becomes immediately smaller after the change to the training phase, but the amplitude increases towards the end of the training phase. With the change to the experimental phase the HF component disappears again and comes back after around 30 seconds. The HF component is present throughout the rest of the experimental phase. It is interesting that that during the BIPs the HF component does not disappear.

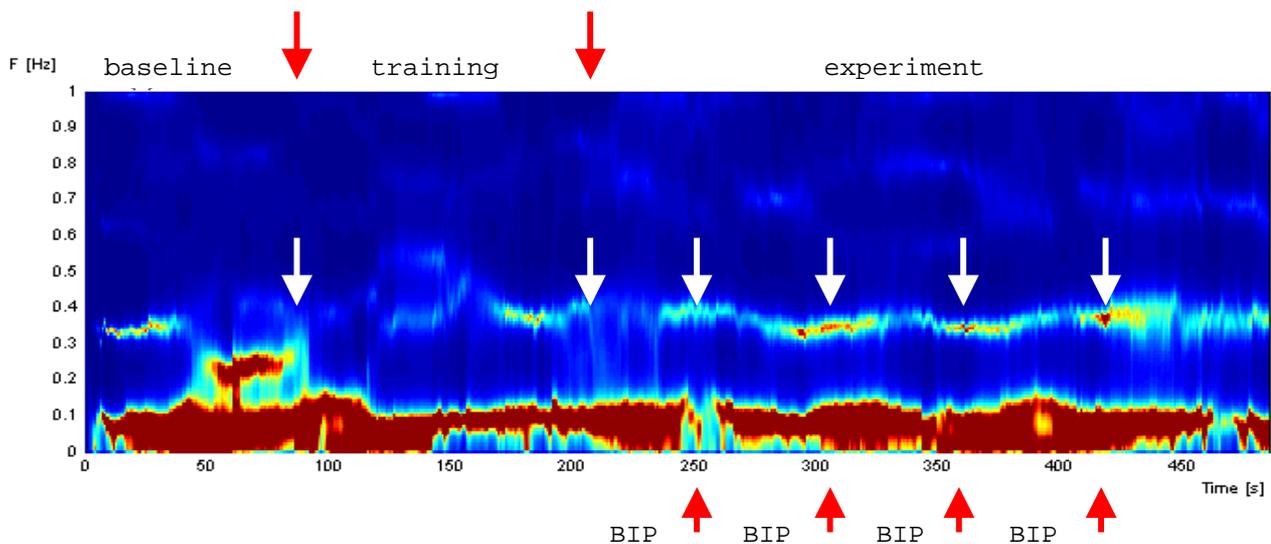


Figure 3: Time/frequency map shows the activation of parasympathetic and sympathetic systems.

Table 2: HRV frequency domain parameters

| HRV | Training | Experimental | p value |
|------------------------|----------|--------------|---------|
| TP [ms ²] | 1560.2 | 1262.3 | |
| ULF [ms ²] | 52.8 | 19.7 | |
| VLF [ms ²] | 202.8 | 86.0 | |
| LF [ms ²] | 1003.0 | 786.1 | |
| HF [ms ²] | 215.9 | 276.4 | |
| LFnorm [n.u.] | 74.5 | 64.9 | 0.0266 |
| HFnorm [n.u.] | 15.1 | 22.3 | 0.0266 |
| LF/HF [1] | 6.9 | 4.0 | 0.0266 |

The change of the HR that was initiated by the speaking avatars was analyzed with the ER-ECG analysis. Therefore, the mean HR immediately before and after each speaking event was calculated. This was done for each speaking event and the results were averaged to show the HR changes for each subject. For the speaker ER-ECG, the most significant change was found for n=3. Figure 4 displays the ER-ECG change of the RR intervals in %. The mean HR increase for all subjects was 0.7 bpm with a p-value of 0.04.

The opposite was the case for the BIPS. The HR decreased by 2.3 bpm because of the BIP (p=0.007). The most significant change was found with n=5. Figure 5 shows again the ER-ECG of the RR intervals in %.

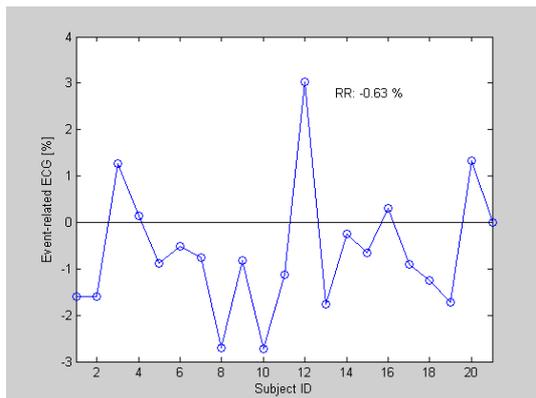


Figure 4: Event-related ECG initiated by the speaking avatar. The y-axis shows the RR change in %, the x-axis the 21 different subjects. The black line at 0% indicates no HR change. In 5 subjects the RR interval increased, which corresponds to a reduction of the HR. The mean decrease of the RR interval was 0.63%.

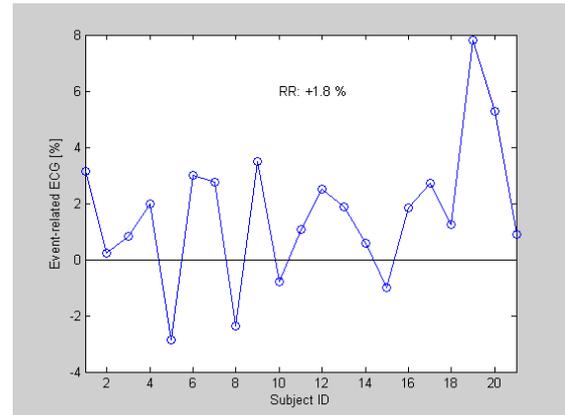


Figure 5: Event-related ECG change initiated by the BIP. The RR interval increased in 17 subjects out of 21. The mean change was +1.8 %.

5. Discussion

The time and frequency parameters display significant changes of HR and HRV between the training and experimental phase. The heart-rate decrease of 5.08 bpm could have 2 reasons:

1. during the training phase the subjects were specifically instructed to move around the VE to practice navigation, whereas in the experimental phase they were free to actively move around the bar or stay still if they preferred;
2. the subjects were more relaxed in the experimental phase when they were in the bar environment.

The HRV displays a high variability in the experimental bar phase. The time domain measures increased: RMSSD by 4.57 ms, SDSD by 4.6 ms, pNN50 by 3.32 % and the SDNNindex by 3.4 ms. In the case of frequency domain measures the LFnorm component decreased by 9.6, the HFnorm component increased by 7.2 and the LF/HF ratio is reduced by 2.9. The time domain difference measures RMSSD, SDSD and pNN50 correlate normally to the HF component in the frequency domain and are also in line in our experiment. RMSSD, SDSD, pNN50 and HFnorm are all increased. The time domain measures SDNN/SDHR correlate with the frequency domain measure TP. All these measures did not show a significant change.

It is well known that during dynamic exercise the HR is increased, but the HF component does not change significantly. In the experiment presented here the heart-rate changed and the HF component changed. Therefore it can be argued that the

change was not initiated by dynamic exercise. Furthermore, an increased LF component and a decreased HF component normally indicate mental stress. This is precisely what happened in the training phases in our experiment, where subjects were more stressed than in the experimental phase. There are several possible explanations: the novelty of the experience of being in a VE, the unfamiliar equipment (including stereoscopic goggles and 3D mouse), and the novelty of entering the bar environment. Conversely, the positive relaxing effect of being in the bar could have caused the changes in HRV and HR.

The most surprising result is the increase of the HR when an avatar speaks to the subjects. In two subjects the ER-ECG of RR intervals was decreased by almost 3 % because of the speaking avatar. In the case of the BIP it is interesting that the HR was decreased because of the BIP. This can be explained by the sudden “whiteout” event, which surprised the subjects and changed their respiration rhythm.

Conclusions

A standard Einthoven I ECG derivation can be used to calculate the HRV and event-related ECG to describe the physiological state of participants in VR environments. HRV is useful to compare different experimental states which last over several minutes. In contrast the event-related ECG can be calculated of intervals of some seconds and reflects changes of HR from a baseline interval to an active interval.

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References

[1] Bernardi, L., Passino, C., Spadacini, G., Calciati, A., Robergs, R., Greene, R., Martignoni, E., Anand, I., Appenzeller, O., Cardiovascular autonomic modulation and activity of carotid baroreceptors at altitude, *Clin. Sci.*, vol. 95, pp. 565-573, 1998.

[2] Frecon, E. And Stenius, M., Dive: A Scaleable Network Architecture For Distributed Virtual Environments, *Distributed Systems Engineering Journal*, vol. 5(3), pp. 91-100, 1998.

[3] Freeman, J., Avons, S.E., Pearson, D.E., Ijsselsteijn, W.A., Effects of sensory information and prior experience on direct subjective ratings of presence, *Presence: Teleoperators and Virtual Environments*, vol. 8(1), pp. 1-13, 1999.

[4] Guger, C., Domej, W., Lindner, G., Pfurtscheller, G., Pfurtscheller, K., Edlinger, G., Effects of a fast cable car ascent to an altitude of 2700 meters on EEG and ECG, *Neuroscience Letters*, submitted, 2004.

[5] Meehan, M. An Objective Surrogate for Presence: Physiological Response. *Presence 2000-3rd International Workshop on Presence*. [online]. Available: <http://www.presence-research.org> (May 29, 2001).

[6] Pan, J., Tompkins, W.J., A real-time QRS detection algorithm, *IEEE Transactions on Biomedical Engineering*, vol. 32, pp. 230-236, 1985.

[7] Slater, M., Steed, A.J., A Virtual Presence Counter, *Presence: Teleoperators And Virtual Environments*, vol. 9(5), pp. 413-434, 2000.

[8] Slater, M., Brogni, A., Steed, A., Physiological Responses To Breaks In Presence: A Pilot Study, *Presence 2003: The 6th Annual International Workshop On Presence*, 2003.

[9] Stoica, P., Moses, R.L., *Introduction to Spectral Analysis*, Prentice-Hall, 1997.

[10] Task Force of the European Society of Cardiology and The North American Society of Pacing and Electrophysiology, Heart rate variability. *Europ. Heart J.*, vol. 17, pp. 354-381, 1996.

[11] Wiederhold, B.K., Davis, R., Wiederhold, M.D. The effect of immersiveness on physiology. In Riva, G., Wiederhold, M.D. (Eds.), *Virtual environments in clinical psychology and neuroscience*. Amsterdam: IOS Press, 1998.

[12] Wiederhold, B.K., Jang, D.P., Kaneda, M., Cabral, I., Lurie, Y., May, T., An investigation into physiological responses in virtual environments: An objective measurement of presence, *Towards CyberPsychology: Mind, Cognitions and Society in the Internet Age*, Amsterdam, IOS Press, pp. 175-183, 2003.