Heart Rate Variability Analysis and Performance during a Repeated Mental Workload Task

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Abstract— **We designed and conducted an experiment using a repetitive task to investigate associations between mental workload, performance, and Heart Rate Variability (HRV) features across repetitions. According to the literature, we define mental workload as the interaction between a person and a task that causes task demands to exceed the person's capacity to deliver. Mental workload was triggered by the use of a highly-paced video game repeated over time. Before engaging with the task, each subject was assessed in controlled condition (i.e., relaxing period) for a short time. Short term HRV features variations between the baseline (i.e., control situation) and each repetitive gaming session (i.e., mental task) were explored. The results show that HRV dynamics diminish with repetitions, while performance increases. Importantly, this suggests that HRV features can be well correlated with performance. Overall, this study advances the use of HRV analysis in the behavioral sciences at large, allowing the design of flexible neurophysiological lab-based experiments. Thus, it also opens the way to future autonomic behavioral neuroscience research.**

Keywords— **HRV, behavioral science, mental workload, mental stress, performance**

I. INTRODUCTION

Several physiological signals (e.g., ECG, EMG, and skin conductance) have been increasingly used in autonomic neuroscience and behavioral science to assess mental workload and attention. Among them, cardiac activity and Heart Rate Variability (HRV) are some of the most investigated signals and methodologies used, respectively. Indeed, research has argued that HRV offers an index of the autonomic nervous system (ANS) activity, useful to investigate valence, arousal, attention, cognitive effort, and stress [1]. For instance, research shows that HRV is reduced as mental workload and attentional demands increase [2]. At the same time, this method allows overcoming sensitivity issues of self-reported approaches (e.g., surveys) in capturing behavioral constructs [3]. Added to this, HRV analysis is non-invasive, wearable, relatively inexpensive, and enables long-term registration, thus being applicable in the laboratory and easily transferable into real-life settings. Leveraging these benefits, HRV has been often used as indicator of mental stress and workload [4].

In this study, we sought to investigate to what extent mental workload can be assessed by measuring HRV variations; we also sought to understand if performance is correlated with changes in HRV features during repeated tasks. Mental workload reflects the mental demand and physiological stress experienced by a subject during a task [5]. Here, mental workload was triggered by repetitive sessions of a highly paced video game. Indeed, video games have been shown to be good settings to trigger mental workload [6].

Put it in other words, this study sought to understand if short term HRV analysis can be a reliable indicator of mental workload inducted by a demanding task, and if performance is associated with changes in HRV features among repeated tasks.

To date, only a few studies [7-10] have attempted to tackle this problem using ECG recordings. For one, Henning et al. [8] show that reduced mental load is associated with slower heart rate (HR) [7]. For another, Lehrer et al. [9] investigate performance of air-pilots, showing that it is negatively correlated with the low-frequency/high-frequency ratio (LF/HF) and with mean HR. Finally, Fairclough et al. [10] investigate trends between physiological signals and performance by using subtasks with increasing demands, and showing that the mean of inter-times among consecutive normal beats (MeanNN) and the vagal tone are lower during high demanding mental tasks. Yet, these studies were generally carried out on only a few subjects, lacking sufficient statistical power.

In the present experiment we tackle this gaps and investigate how mental workload affects HRV over repeated video gaming sessions in 54 subjects. As a secondary outcome, we also aim to demonstrate to what extent HRV features are correlated with performance over time in the context of our repeated task.

II. METHODS AND MATERIAL

A. Study Participants

69 healthy subjects (32 females; age: 26±2.2 years) with no history of heart disease, systemic hypertension, or other conditions potentially influencing HRV analysis were enrolled in this study. They were not obese and did not take medication, drugs, or alcohol in the 12 hours preceding the

experiment. All subjects were right handed with normal vision, frequent computers users (i.e., daily), and skilled at operating mouse and keyboard. None of the subjects included in our current analysis was familiar with video games. The Biomedical and Scientific Research Ethics Committee of the University of Warwick approved this study (ref. REGO-2014-656 AMO1), assuring anonymity and no side effects or possible disadvantages for the subjects. All subjects were carefully instructed and informed consent was acquired prior to the experiment. Subjects were compensated with a fixed show-up fee.

B.Protocol

The study was conducted in the Behavioral Science Laboratory of the Warwick Business School under controlled conditions: a quiet room, at a comfortable temperature, at the same hour in the morning. They were instructed to sit comfortably on an armchair and were assisted in wearing a BioPatch™ M3 device (Zephyr, Annapolis, USA) to record the ECG.

Continuous ECG recording was performed during baseline (i.e., control condition) and mental task (i.e., four video gaming sessions). A 60 s break was taken between sessions. The baseline session was recorded for 5 minutes in which the participants were asked to complete a computer-based survey on demographic and anthropometric information (i.e. age, gender weight, height, and handedness) (Fig 1). Before the video game started, the researchers presented each participant with a brief introduction on the game's instructions. The video game was administered repetitively on a 24'' PC monitor for 5 nominal minutes per session.

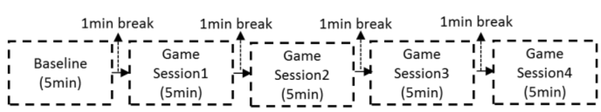

Fig. 1 Study protocol

C.Video Game

A highly-paced one-person shooter video game containing some violent content (i.e., war scenes and gun fighting), ranked as suitable to people above 16 years, was used as trigger of mental workload. Highly-paced video games have shown to be a reliable method to elicit mental workload [6]. The video game was played as a repetitive task (i.e., four sessions). This was done in order to investigate the impact of mental workload on HRV, as well as any correlation between HRV and performance over time. The main challenge posed to participants during the sessions was to complete a mission by killing as many enemies as possible. The performance for each game session was computed directly by the video game as the number of enemies killed per session.

D.HRV Analysis

The RR interval time-series was extracted from ECG records using an automatic QRS detector, WQRS, available in the PhysioNet's toolkit [11]. QRS review and correction was performed using PhysioNet's WAVE. The fraction of total RR intervals labelled as normal-to-normal (NN) intervals was computed as NN/RR ratio. NN/RR ratio was then used to measure the reliability of the data. Records with NN/RR ratio less than 90% threshold were excluded from the analysis. HRV analysis was performed on 5 min excerpts using Kubios (version 2.2) [12]. Time and frequency-domain features were analyzed according to international guidelines [13], while non-linear measures were analyzed as described in [14]. Frequency domain features were extracted from power spectrum estimated with autoregressive (AR) model methods [12]. Finally, 20 HRV features were examined (Table 1).

Table 1. HRV features analyzed in the study

HRV Measures	Units	Description
MeanNN	[ms]	The mean of RR intervals
StdNN	[ms]	Standard deviation of RR intervals
RMSSD	[ms]	Square root of the mean squared differences between successive RR intervals
NN50	-	Number of successive RR interval pairs that differ more than 50 s
pNN50	[%]	NN50 divided by the total number of RR intervals
Absolute power	[ms^2]	Absolute powers of LF(0.04-0.15Hz) and HF bands(0.15-0.4 Hz)
LF/HF	-	Ratio between LF and HF band powers
sd1, sd2	[ms]	The standard deviation of the Poincare' plot perpendicular to (SD1) and along (SD2)the line-of-identity
Apen	-	Approximate Entropy
Sampen	-	Sample entropy
d2	-	Correlation dimension
dfa1, dfa2	-	Detrented fluctuation analysis: Short term and Long term fluctuation slope
RPlmean	[beats]	Recurrence plot analysis: Mean line length
RPlmax	[beats]	Recurrence plot analysis: Maximum line length
REC	[%]	Recurrence rate
RPadet	[%]	Recurrence plot analysis: Determinism
ShanEn	-	Shannon entropy

E.Statistical, Trend and Correlation Analysis

Because HRV features were found non-normally distributed, Median (MD), Median Absolute Deviation (MAD) and interquartile range (IQR) (i.e., non-parametric descriptors) were computed for each repetition. The non-parametric Wilcoxon Signed-Rank Test was used to appreciate statistical differences of HRV features variation between the baseline (i.e., control situation) and each repetitive task (i.e., video game sessions). Comparisons among sessions were performed using a Kruskal-Wallis test.

The trends of MD for HRV features were also reported using the convention proposed in [4]:

- two arrows, ↓↓ (or ↑↑), were used to report a significant (p<0.05) decrease (or increase) of one feature during the game session;
- one arrow was used for non-significant variations: ↓ (or ↑) indicated a non-significant (p>.05) decrease (or increase) of a measure during the game session.

Moreover, for exploratory purposes, the MD was plotted along the performance per game session (i.e., number of points) per each HRV feature. MD and performance were normalized to their maximum and the trends between HRV features and performance investigated. Spearman's correlation coefficients (*rho*) between each HRV feature and performance over the four sessions were computed. A HRV feature and performance were considered highly correlated if *rho* resulted greater than 0.7 and significant if the associated p-value was less than 0.05.

III. Results and Discussion

Data for 54 participants were included in the current study. ECG signals for 15 participants were discarded after quality check (i.e., NN/RR ratio < 90%).

Table 2 shows the p-value and HRV trend between the repeated video gaming sessions (i.e., mental workload) and the baseline (i.e., control condition). Seven HRV features changed significantly between session 1 and the baseline (see column 2: GS1 vs. B). In particular, MeanNN, SdNN, LF, sd2 and dfa1 decreased significantly, while Apen and Sampen increased significantly. As shown in the other columns of Table 2, in GS2-4 more HRV features changed significantly relatively to the baseline (see HRV features 8, 10, and 11 respectively).

All the HRV features maintained similar trends over the four sessions, reflecting consistency of HRV fluctuation as the task progressed. Yet, the number of non-linear HRV features showing to be significantly different increased moving from session 1 to session 4. Indeed, non-linear HRV features 4, 5, 7 and 9 changed in game 1, 2, 3 and 4 respectively. This overall reflects an increasingly depressed HRV during each repetition, suggesting an increase in stress [4]. By comparing within sessions, dfa2 and RPadet were found significantly different between session 1 and 4, while ShanEn between session 3 and 4. Previous studies [15-17], showed that as one task's demand increases, HRV becomes more depressed. Added to this, here we found that also on repetitive tasks, there is a depressed HRV over sessions, which is possibly due to an increase in mental workload.

Fig. 2 shows the correlation coefficients between normalized HRV features and performance over the four game sessions. Fig. 2 shows that performance increased over sessions overall. We reasoned that this occurred because players tend to perform better once become more familiar with the video game; this finding is also in agreement with previous studies showing similar rates at which people improve through practice [18]. Noteworthy, eight HRV features presented high correlation with performance over the four sessions. Aside from MeanNN, all the remaining HRV features showed a negative correlation with performance over sessions. Yet, the p-value of those correlations was higher than 0.05, possibly because of the limited amount of repetitions.

Table 2. HRV Analysis

HRV	GS1 vs B		GS2 vs B		GS3 vs B		GS4 vs B	
Features	p-val	Tr	p-val	Tr	p-val	Tr	p-val	Tr
MeanNN	**0.029**	↓↓	0.121	↓	0.405	↓	0.608	↓
StdNN	**0.002**	↓↓	**0.000**	↓↓	**0.000**	↓↓	**0.000**	↓↓
RMSSD	0.144	↓	0.080	↓	0.119	↓	0.227	↓
NN50	0.277	↓	0.077	↓	0.140	↓	0.190	↓
pNN50	0.177	↓	0.058	↓	0.123	↓	0.175	↓
LF	**0.001**	↓↓	**0.001**	↓↓	**0.000**	↓↓	**0.000**	↓↓
HF	0.053	↓	**0.009**	↓↓	**0.006**	↓↓	**0.004**	↓↓
LF/HF	0.412	↓	0.706	↓	0.724	↓	0.080	↓
sd1	0.144	↓	0.080	↓	0.119	↓	0.227	↓
sd2	**0.001**	↓↓	**0.000**	↓↓	**0.000**	↓↓	**0.000**	↓↓
Apen	**0.008**	↑↑	**0.001**	↑↑	**0.001**	↑↑	**0.003**	↑↑
Sampen	**0.018**	↑↑	**0.000**	↑↑	**0.000**	↑↑	**0.000**	↑↑
d2	0.747	↓	0.517	↓	0.118	↓	0.270	↓
dfa1	**0.026**	↓↓	0.115	↓	0.102	↓	**0.010**	↓↓
dfa2	0.052	↓	**0.011**	↓↓	**0.028**	↓↓	**0.007**[a]	↓↓
RPlmean	0.196	↓	0.076	↓	0.093	↓	**0.005**	↓↓
RPlmax	0.103	↓	0.236	↓	**0.045**	↓↓	0.076	↓
REC	0.078	↓	0.059	↓	**0.027**	↓↓	**0.003**	↓↓
RPadet	0.060	↓	**0.012**	↓↓	**0.002**	↓↓	**0.000**[a]	↓↓
ShanEn	0.158	↓	0.107	↓	0.114	↓	**0.006**[b]	↓↓

Tr: Trend; p-val: p-value; GS1-4: Game Sessions 1-4; B: Baseline; ↓↓ (↑↑): significantly lower (higher) under mental workload (p<.05);↓(↑): lower (higher) under mental workload (p>.05); [a] significant different between GS1 and GS4; [b] significant different between GS3 and GS4.

IV. Conclusions

In this study, we investigated the effects of mental workload induced by a repetitive task on HRV features. We found that over repetitions, a depressed HRV accentuates as repetitions progress. This is likely correlated with the increase in the mental workload. Moreover, we found a correlation between task performance and key HRV features.

All in all, this study opens novel opportunities for research at the interface between HRV analysis and behavioral science in both lab-based and real-life settings. This also is potentially able to foster the autonomic neuroscience research agenda.

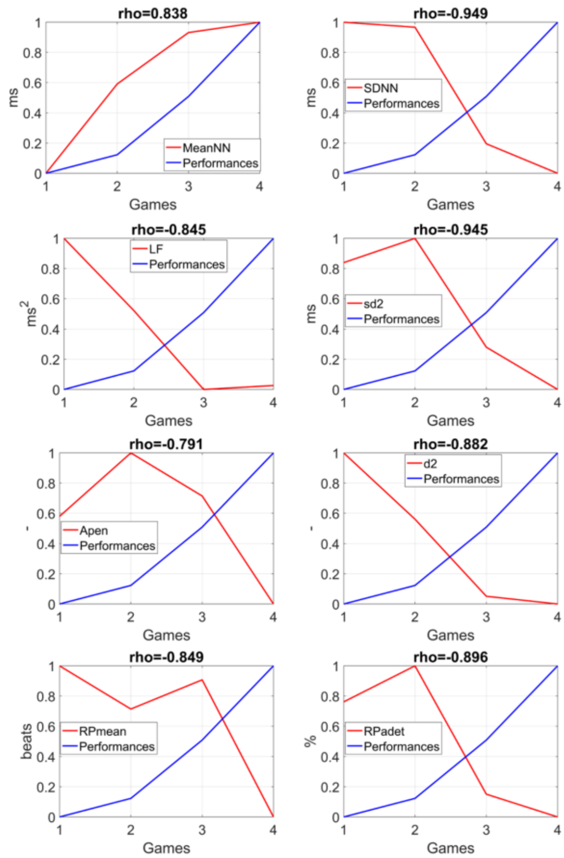

Fig. 2 Trend Analysis and Correlation Coefficients of HRV features and performance.

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Conflict of Interest

The authors declare no conflicts of interest.

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