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AURUM MÜHENDİSLİK SİSTEMLERİ VE MİMARLIK DERGİSİ
AURUM JOURNAL OF ENGINEERING SYSTEMS AND ARCHITECTURE

Cilt 8, Sayı 2 | Kış 2024
Volume 8, No 2| Winter 2024

HEART RATE VARIABILITY IN ATHLETES DURING A VIRTUAL REALITY-BASED WORKING MEMORY EXPERIENCE

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Received: 13.06.2024
Accepted: 13.06.2024
Published: 31.12.2024
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Research Article
pp.207-234
DOI: 10.53600/ajesa.1500658

Abstract

The study explores the link between cognitive performance and heart rate variability (HRV) using a virtual reality (VR) cognitive assessment system by Neo Auvra® Digital Health and Bionics Technologies Inc. All participants underwent varying levels of mental workload in the VR environment, with metrics like Verbal Working Memory Capacity Item Number (VeWMCIN), Visuospatial Working Memory Capacity Item Number (ViWMCIN), Working Memory Efficiency Task Switching Speed (WMETSS), and Visual Attention Accuracy (VAA). Heart Rate Variability (HRV) data was collected during VR session from two groups: athletes and sedentary individuals. Multivariate analysis of variance (MANOVA) was employed. When analyzing the results of the study, it was concluded that HRV parameters did not differ significantly (according to p-value) or significantly (according to 95% Cis and effect sizes) between different levels (cognitive load), HRV parameters showed significant (according to p-value) and significant (according to 95% Cis and effect sizes) differences between different groups, while athletes had better values in all HRV parameters except HF%, LF%, IF%.

Keywords: Heart Rate Variability, Virtual Reality, Cognitive Performance, Athletes, Working Memory

HEART RATE VARIABILITY IN ATHLETES DURING A VIRTUAL REALITY-BASED WORKING MEMORY EXPERIENCE

Özet

Araştırma, Neo Auvra® Digital Health and Bionics Technologies Inc. tarafından geliştirilen sanal gerçeklik (VR) bilişsel değerlendirme sistemi kullanılarak bilişsel performans ile kalp atım hızı değişkenliği (HRV) arasındaki ilişkiyi incelemektedir. Tüm katılımcılar, sanal gerçeklik (VR) ortamında değişen düzeylerde aynı zihinsel iş yüküne maruz kalmışlardır. VR ortamında; Verbal Working Memory Capacity Item Number (VeWMCIN), Visuospatial Working Memory Capacity Item Number (ViWMCIN), Working Memory Efficiency Task Switching Speed (WMETSS) ve Visual Attention Accuracy (VAA) gibi ölçütler kullanılmıştır. HRV verileri, sporcular ve sedanter bireyler olmak üzere iki gruptan VR oturumları sırasında toplanmıştır. Çoklu değişken varyans analizi (MANOVA) kullanılmıştır. Çalışmanın sonuçlarını analiz ederken, HRV parametrelerinin farklı düzeyler arasında (bilişsel yük) anlamlı bir şekilde farklılık göstermediği sonucuna varılmıştır, ancak HRV parametrelerinin farklı gruplar arasında anlamlı farklılıklar gösterdiği; sporcuların, HF%, LF% ve IF% hariç tüm HRV parametrelerinde daha iyi değerlere sahip olduğu belirlenmiştir.

Anahtar Kelimeler: Kalp Atış Hızı Değişkenliği, Sanal Gerçeklik, Bilişsel Performans, Atletler, İşler Bellek

1. Introduction

An integrative health model acknowledges cognitive, emotional, behavioral, and physiological factors influencing individual differences. Studies increasingly highlight electrophysiological findings' role in understanding cognitive performance. HRV reflects autonomic nervous system (ANS) activity, comprising the sympathetic (SNS) and parasympathetic (PNS) branches. Time-domain indices like SDNN, RMSSD, and pNN50, and frequency-domain indices (e.g., TP, VLF, LF, HF) derived from HRV data analysis provide insights into cognitive functions like attention and memory performance (Forte et al., 2019, Laborde et al., 2017, Shaffer et al., 2017).

Table 1. Traditional HRV time domain and frequency domain measurements and heart rate fragmentation measurements.

Parameter	Unit	Description
SDNN	ms	Standard deviation of NN intervals
pNN50	%	Percentage of successive RR intervals that differ by more than 50 ms
RMSSD	ms	Root mean square of successive RR interval differences
ULF power	ms^2	Absolute power of the ultra-low-frequency band (=0.003 Hz)
VLF power	ms^2	Absolute power of the very-low frequency band (0.0033-0.04 Hz)
LF power	ms^2	Absolute power of the low-frequency band (0.04-0.15 Hz)
LF power	nu	Relative power of the low-frequency band (0.04-0.15 Hz) in normal units
HF power	ms^2	Absolute power of the high-frequency band (0.15-0.4 Hz)
HF power	nu	Relative power of the high-frequency band (0.15-0.4 Hz) in normal suits.
LF/HF	%	Ratio of LF-to-HF power
PIP	%	Percentage of inflection points for R-R interval

Shaffer & Ginsberg (2017).

Understanding the connection between physiological and psychological aspects notably decreased Heart Rate Variability (HRV), is crucial for managing cognitive function and enhancing disease management (Hilgarter et al., 2021). While conflicting findings exist, most studies suggest a decrease in HRV with increased cognitive load (Muthukrishnan et al., 2017). However, the relationship between HRV and cognitive function remains incompletely understood (Nicolini et al., 2020), with Muthukrishnan et al. (2017) highlighting an inverse relationship between memory load and HRV, suggesting HRV as an indicator of cognitive capacity.

Virtual Reality (VR) technology improves cognitive performance assessment by providing realistic environments (Wang, 2012). It's particularly useful in sports science, offering new methods for assessing athletic performance (Neumann et al., 2018). Optimal cognitive functioning is essential for peak sports performance, with physical exercise positively impacting cognitive function and well-being (Walton et al., 2018; Mandolesi et al., 2018).

2. Methods

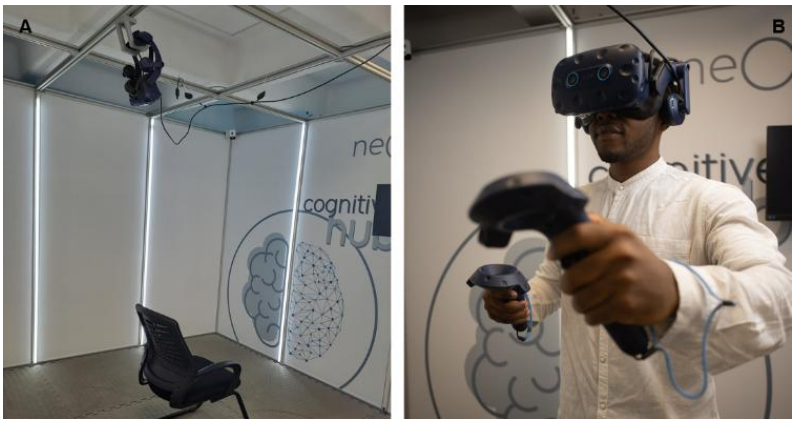
Based on studies emphasizing that the cognitive performance of athletes is better than that of sedentary individuals, this study investigated the cognitive performance of two different groups of athletes and sedentary individuals. All participants were exposed to mental workload tasks of varying difficulty in a VR-based system. HRV data were also recorded from all participants during the VR experience. The aim of the present study is to investigate whether the cognitive performance of individuals, obtained by mental workload tasks performed at different groups (athletes and control group), has an effect on HRV data.

This research is a retrospective study conducted using data from a study with protocol code 09.2022.606, which obtained ethical approval on 10.05.2022.

The study included 16 participants aged 18 to 55, divided into athletes (7) and a control group (9). Athletes were triathlon competitors, while the control group comprised sedentary executives. All participants signed consent forms and completed pre-experiment questionnaires on various factors. They were briefed on the VR experience and measurements. Measurements took place in a controlled, insulated room at the Neo Auvra® Measurement Center. Participants wore a heart rate monitor band (Polar H10) and used HTC Vive Pro Eye HMD controllers. The room where the measurements were conducted was of insulated nature, and only the participant and research staff were present in the measurement area during the measurement. The measurements were conducted at the Neo Auvra® Measurement Center. During the measurement, the participant was positioned at the center of the measurement room, which was 3m x 3m in size (**Photograph 1**), thus ensuring equal access to every area during the VR experience. The heart rate monitor band, one of the measurement tools, was connected to the participant before the VR experience, and the recording was started and stopped simultaneously with the VR experience.

All participants experienced the Neo Auvra® product named NORA VRx™- Core in the VR environment.

The product, developed in the Unreal Engine game engine, lasts approximately 15-20 minutes.



Photograph 1: A) Experiment room. **B)** A participant experiences the VR experience.

The VR experience consists of seven levels, with the first two levels being the learning phase of the experience and not included in the cognitive assessment phase. The learning phase lasts an average of 5-8 minutes, during which participants are introduced to the VR environment and are practiced on the tasks they will encounter during the experience. After completing the learning phase, participants continued to the other steps of the VR experience without any guidance from the research staff and completed the tasks. Each participant successfully completed every step of the experience. The explanations of the metrics and levels in the VR environment are presented in **Figure 1**.

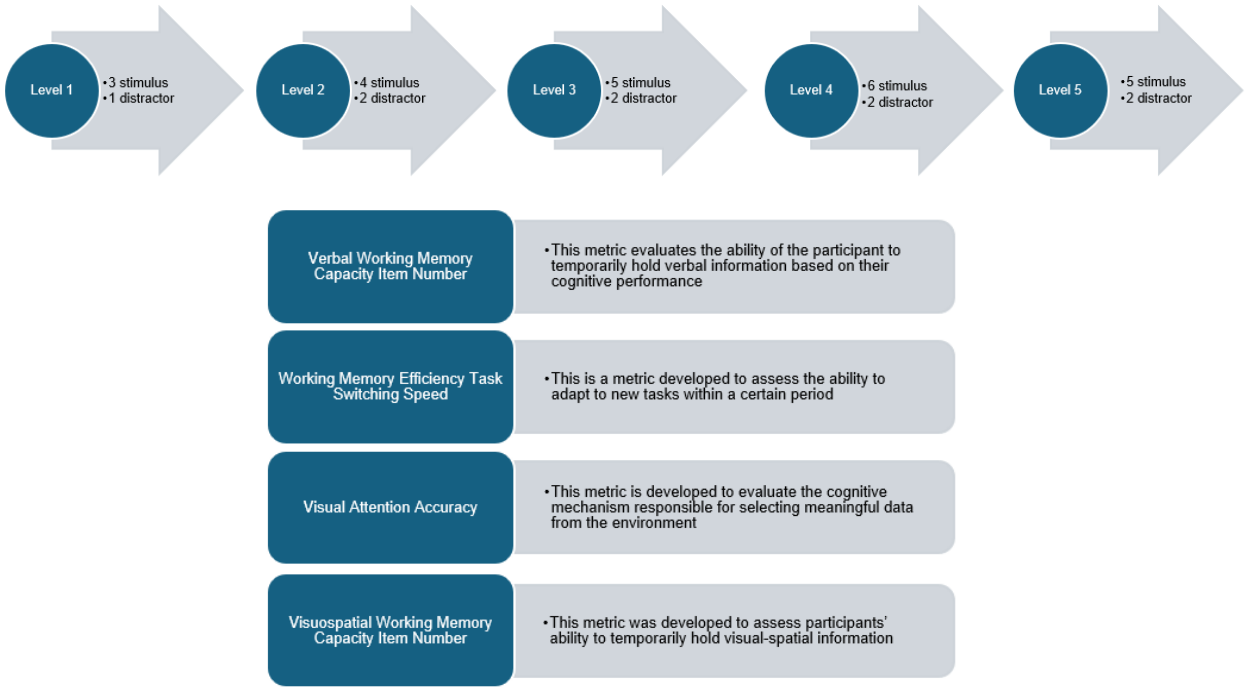


Figure 1: Levels and metrics calculated in VR

The study employed a Multivariate Analysis of Variance (MANOVA) due to multiple dependent variables. MANOVA assesses if there are differences between groups based on an independent variable. It aimed to analyze how different difficulty levels of VR experiences and participant groups (athletes vs. controls) affect HRV values. Statistical analyses were conducted using SPSS Version 29.0.0.0. First, data equality of variance was assessed. Then, the effects of participant groups and VR difficulty levels on HRV values were examined. Post hoc tests were selected based on analysis data to detail the effects of dependent variables.

3. Results

In the present study there are two different groups, the athletes and the control group. The relationship between the groups and the dependent variables, HRV parameters, is shown in **Table 2**. In this table, the HRV parameters in the time and frequency domain were evaluated separately as dependent variables. According to the values in the table, there is a significant change in HRV mean, HRV min, HRV max, SDNN, RMSSD, and pnn50 parameters related to the time domain of HRV according to the groups. No significant changes were observed in the levels of VR experience and in the time and frequency domain parameters of HRV.

Multivariate Tests[a]

Effect		Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[d]
Intercept	Pillai's Trace	.998	4645.186[b]	9.000	87.000	<.001	.998	41806.676	1.000
	Wilks' Lambda	.002	4645.186[b]	9.000	87.000	<.001	.998	41806.676	1.000
	Hotelling's Trace	480.537	4645.186[b]	9.000	87.000	<.001	.998	41806.676	1.000
	Roy's Largest Root	480.537	4645.186[b]	9.000	87.000	<.001	.998	41806.676	1.000
Groups	Pillai's Trace	.445	7.757[b]	9.000	87.000	<.001	.445	69.811	1.000
	Wilks' Lambda	.555	7.757[b]	9.000	87.000	<.001	.445	69.811	1.000
	Hotelling's Trace	.802	7.757[b]	9.000	87.000	<.001	.445	69.811	1.000
	Roy's Largest Root	.802	7.757[b]	9.000	87.000	<.001	.445	69.811	1.000
Level	Pillai's Trace	.354	.971	36.000	360.000	.521	.088	34.948	.901
	Wilks' Lambda	.684	.969	36.000	327.767	.523	.090	32.583	.868
	Hotelling's Trace	.407	.967	36.000	342.000	.528	.092	34.798	.898
	Roy's Largest Root	.191	1.911[c]	9.000	90.000	.060	.160	17.195	.801
Groups * Level	Pillai's Trace	.214	.565	36.000	360.000	.981	.053	20.323	.605
	Wilks' Lambda	.799	.561	36.000	327.767	.981	.054	18.889	.558
	Hotelling's Trace	.235	.559	36.000	342.000	.982	.056	20.121	.597

	Roy's Largest Root	.139	1.385[c]	9.000	90.000	.207	12.468	.633

a. Design: Intercept + Groups + Level + Groups * Level

b. Exact statistic

c. The statistic is an upper bound on F that yields a lower bound on the significance level.

d. Computed using alpha = .05

When analyzing **Table 3**, the equality of variances data is observed. According to the detailed analyses in the table, the assumption of equality of variances is met. Therefore, it is considered appropriate to apply the LSD post hoc test to examine the effects of groups and different levels of VR experience on HRV values.

Table 3. Levene's Test of Equality of Error Variances

Levene's Test of Equality of Error Variances[a]

		Levene Statistic	df1	df2	Sig.
HRV_mean	Based on Mean	.315	9	95	.968
	Based on Median	.242	9	95	.987
	Based on Median and with adjusted	.242	9	93.263	.987
	Based on trimmed mean	.324	9	95	.965
HRV_min	Based on Mean	.389	9	95	.938
	Based on Median	.184	9	95	.995
	Based on Median and with adjusted	.184	9	87.633	.995
	Based on trimmed mean	.363	9	95	.950
HRV_max	Based on Mean	.671	9	95	.733
	Based on Median	.598	9	95	.796
	Based on Median and with adjusted	.598	9	93.022	.795
	Based on trimmed mean	.678	9	95	.727
SDNN	Based on Mean	.697	9	95	.710
	Based on Median	.467	9	95	.894
	Based on Median and with adjusted	.467	9	57.659	.891
	Based on trimmed mean	.621	9	95	.776
RMSSD	Based on Mean	4.995	9	95	<.001
	Based on Median	2.615	9	95	.010
	Based on Median and with adjusted	2.615	9	40.514	.018
	Based on trimmed mean	4.905	9	95	<.001
	Based on Mean	15.020	9	95	<.001

pnn50	Based on Median	5.583	9	95	<.001
	Based on Median and with adjusted	5.583	9	34.188	<.001
	Based on trimmed mean	14.139	9	95	<.001
LF%	Based on Mean	1.201	9	95	.303
	Based on Median	.667	9	95	.737
	Based on Median and with adjusted	.667	9	38.727	.733
	Based on trimmed mean	.920	9	95	.512
HF%	Based on Mean	.953	9	95	.483
	Based on Median	.694	9	95	.712
	Based on Median and with adjusted	.694	9	53.578	.711
	Based on trimmed mean	.833	9	95	.588
IF%	Based on Mean	.834	9	95	.586
	Based on Median	.765	9	95	.649
	Based on Median and with adjusted	.765	9	81.853	.649
	Based on trimmed mean	.838	9	95	.583

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Groups + Level + Groups * Level

Table 4. Test of between HRV parameters based on the cognitive load (levels) and groups

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Groups	HRV_mean	4771.670	1	4771.670	24.089	<.001	.202
	HRV_min	5717.346	1	5717.346	37.310	<.001	.282
	HRV_max	3241.620	1	3241.620	13.938	<.001	.128
	SDNN	12914.444	1	12914.444	43.313	<.001	.313
	RMSSD	7128.569	1	7128.569	61.440	<.001	.393
	pnn50	2590.317	1	2590.317	50.223	<.001	.346
	LF%	.016	1	.016	.880	.351	.009
	HF%	.001	1	.001	.102	.750	.001

	IF%	.000	1	.000	.104	.748	.001
Level	HRV_mean	17.940	4	4.485	.023	.999	.001
	HRV_min	244.606	4	61.152	.399	.809	.017
	HRV_max	86.044	4	21.511	.092	.985	.004
	SDNN	884.131	4	221.033	.741	.566	.030
	RMSSD	116.443	4	29.111	.251	.908	.010
	pnn50	23.609	4	5.902	.114	.977	.005
	LF%	.090	4	.022	1.246	.297	.050
	HF%	.011	4	.003	.237	.917	.010
	IF%	.025	4	.006	1.587	.184	.063
Groups * Level	HRV_mean	2.854	4	.713	.004	1.000	.000
	HRV_min	27.273	4	6.818	.044	.996	.002
	HRV_max	22.844	4	5.711	.025	.999	.001
	SDNN	320.400	4	80.100	.269	.897	.011
	RMSSD	40.309	4	10.077	.087	.986	.004
	pnn50	39.360	4	9.840	.191	.943	.008
	LF%	.043	4	.011	.594	.668	.024
	HF%	.015	4	.004	.322	.862	.013
	IF%	.028	4	.007	1.744	.147	.068

This table shows the detailed comparisons of the HRV parameters based on the group selection (athletes - 1vs nonathletes -0).

Table 5. Multiple Comparisons of Groups and Dependent Variables

Pairwise Comparisons among Groups							
						95% Confidence Interval for Difference[b]	
Dependent Variable	(I) Groups	(J) Groups	Mean Difference (I-J)	Std. Error	Sig.[b]	Lower Bound	Upper Bound
HRV_mean	0	1	13.622*	2.776	<.001	8.112	19.132
	1	0	-13.622*	2.776	<.001	-19.132	-8.112
HRV_min	0	1	14.911*	2.441	<.001	10.065	19.757
	1	0	-14.911*	2.441	<.001	-19.757	-10.065
HRV_max	0	1	11.228*	3.007	<.001	5.257	17.198
	1	0	-11.228*	3.007	<.001	-17.198	-5.257
SDNN	0	1	-22.410*	3.405	<.001	-29.171	-15.650
	1	0	22.410*	3.405	<.001	15.650	29.171
RMSSD	0	1	-16.650*	2.124	<.001	-20.867	-12.433
	1	0	16.650*	2.124	<.001	12.433	20.867
pnn50	0	1	-10.037*	1.416	<.001	-12.848	-7.225
	1	0	10.037*	1.416	<.001	7.225	12.848
LF%	0	1	.025	.026	.351	-.028	.077
	1	0	-.025	.026	.351	-.077	.028
HF%	0	1	-.007	.021	.750	-.049	.035
	1	0	.007	.021	.750	-.035	.049
IF%	0	1	.004	.012	.748	-.021	.029
	1	0	-.004	.012	.748	-.029	.021

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

Table 4 shows the effects of HRV parameters, while **Table 5** presents their impact on different groups. Pairwise comparisons reveal significant differences in HRV mean, min, max, SDNN, RMSSD, and pnn50 between groups. SDNN has the most pronounced effect, with the control group exhibiting the highest impact compared to athletes. However, LF%, HF%, and L/H% show no group effect.

The study included VR experiences with 5 progressively difficult levels of cognitive load. **Table 6** illustrates how these difficulty levels relate to HRV parameters in both time and frequency domains.

Table 6. Examination of changes in HRV values depending on the levels of VR experience

Estimates Levels					
				95% Confidence Interval for Difference	
Dependent Variable	Level	Mean	Std. Error	Lower Bound	Upper Bound
HRV_mean	1	84.208	3.103	78.048	90.369
	2	83.375	3.103	77.215	89.535
	3	83.903	3.103	77.742	90.063
	4	83.014	3.103	76.853	89.174
	5	83.778	3.103	77.617	89.938
HRV_min	1	72.208	2.729	66.790	77.627
	2	72.097	2.729	66.679	77.516
	3	72.069	2.729	66.651	77.488
	4	69.333	2.729	63.915	74.752
	5	68.681	2.729	63.262	74.099
HRV_max	1	95.361	3.362	88.686	102.036

	2	93.875	3.362	87.200	100.550
	3	95.000	3.362	88.325	101.675
	4	94.389	3.362	87.714	101.064
	5	96.556	3.362	89.880	103.231
SDNN	1	45.723	3.807	38.165	53.281
	2	48.318	3.807	40.760	55.876
	3	45.108	3.807	37.550	52.666
	4	49.310	3.807	41.752	56.868
	5	53.314	3.807	45.756	60.873
RMSSD	1	22.576	2.375	17.861	27.291
	2	24.628	2.375	19.913	29.342
	3	23.626	2.375	18.911	28.340
	4	25.119	2.375	20.404	29.833
	5	25.507	2.375	20.792	30.222
pnn50	1	5.785	1.583	2.642	8.929
	2	7.156	1.583	4.012	10.299
	3	6.718	1.583	3.575	9.862
	4	6.097	1.583	2.954	9.241
	5	6.320	1.583	3.176	9.463
LF%	1	.668	.030	.610	.727
	2	.710	.030	.651	.769
	3	.724	.030	.665	.782

	4	.751	.030	.692	.809
	5	.681	.030	.622	.740
HF%	1	.167	.024	.120	.213
	2	.160	.024	.113	.207
	3	.165	.024	.118	.212
	4	.143	.024	.097	.190
	5	.174	.024	.127	.221
IF%	1	.129	.014	.102	.157
	2	.161	.014	.134	.189
	3	.169	.014	.141	.196
	4	.173	.014	.145	.200
	5	.151	.014	.124	.179

The table compares HRV parameters across VR experience levels. HRV mean and min values showed no significant differences, all within the 95% confidence interval. HRV max had no differences except for level 5. SDNN showed no significant differences, except between levels 3 and 1. However, RMSSD varied across all levels, and pnn50 differed between VR levels. In the frequency domain, significant differences were observed in LF% and LF/HF% values within the 95% confidence interval.

Table 7. Relationship of HRV parameters according to different levels

Pairwise Comparisons Levels							
						95% Confidence Interval for Difference[b]	
Dependent Variable	(I) Level	(J) Level	Mean Difference (I-J)	Std. Error	Sig.[b]	Lower Bound	Upper Bound
HRV_mean	1	2	.833	4.388	.850	-7.879	9.546
		3	.306	4.388	.945	-8.407	9.018

		4	1.194	4.388	.786	-7.518	9.907
		5	.431	4.388	.922	-8.282	9.143
	2	1	-.833	4.388	.850	-9.546	7.879
		3	-.528	4.388	.905	-9.240	8.184
		4	.361	4.388	.935	-8.351	9.073
		5	-.403	4.388	.927	-9.115	8.309
	3	1	-.306	4.388	.945	-9.018	8.407
		2	.528	4.388	.905	-8.184	9.240
		4	.889	4.388	.840	-7.823	9.601
		5	.125	4.388	.977	-8.587	8.837
	4	1	-1.194	4.388	.786	-9.907	7.518
		2	-.361	4.388	.935	-9.073	8.351
		3	-.889	4.388	.840	-9.601	7.823
		5	-.764	4.388	.862	-9.476	7.948
	5	1	-.431	4.388	.922	-9.143	8.282
		2	.403	4.388	.927	-8.309	9.115
		3	-.125	4.388	.977	-8.837	8.587
		4	.764	4.388	.862	-7.948	9.476
HRV_min	1	2	.111	3.860	.977	-7.552	7.774
		3	.139	3.860	.971	-7.524	7.802
		4	2.875	3.860	.458	-4.788	10.538
		5	3.528	3.860	.363	-4.135	11.190

	2	1	-.111	3.860	.977	-7.774	7.552
		3	.028	3.860	.994	-7.635	7.690
		4	2.764	3.860	.476	-4.899	10.427
		5	3.417	3.860	.378	-4.246	11.079
	3	2	-.139	3.860	.971	-7.802	7.524
		3	-.028	3.860	.994	-7.690	7.635
		4	2.736	3.860	.480	-4.927	10.399
		5	3.389	3.860	.382	-4.274	11.052
	4	1	-2.875	3.860	.458	-10.538	4.788
		2	-2.764	3.860	.476	-10.427	4.899
		3	-2.736	3.860	.480	-10.399	4.927
		5	.653	3.860	.866	-7.010	8.315
	5	1	-3.528	3.860	.363	-11.190	4.135
		2	-3.417	3.860	.378	-11.079	4.246
		3	-3.389	3.860	.382	-11.052	4.274
		4	-.653	3.860	.866	-8.315	7.010
HRV_max	1	2	1.486	4.755	.755	-7.954	10.926
		3	.361	4.755	.940	-9.079	9.801
		4	.972	4.755	.838	-8.468	10.412
		5	-1.194	4.755	.802	-10.634	8.246
	2	1	-1.486	4.755	.755	-10.926	7.954
		3	-1.125	4.755	.813	-10.565	8.315

		4	-.514	4.755	.914	-9.954	8.926
		5	-2.681	4.755	.574	-12.121	6.759
	3	1	-.361	4.755	.940	-9.801	9.079
		2	1.125	4.755	.813	-8.315	10.565
		4	.611	4.755	.898	-8.829	10.051
		5	-1.556	4.755	.744	-10.996	7.884
	4	1	-.972	4.755	.838	-10.412	8.468
		2	.514	4.755	.914	-8.926	9.954
		3	-.611	4.755	.898	-10.051	8.829
		5	-2.167	4.755	.650	-11.607	7.273
	5	1	1.194	4.755	.802	-8.246	10.634
		2	2.681	4.755	.574	-6.759	12.121
		3	1.556	4.755	.744	-7.884	10.996
		4	2.167	4.755	.650	-7.273	11.607
SDNN	1	2	-2.595	5.384	.631	-13.284	8.094
		3	.615	5.384	.909	-10.074	11.304
		4	-3.587	5.384	.507	-14.276	7.102
		5	-7.591	5.384	.162	-18.280	3.097
	2	1	2.595	5.384	.631	-8.094	13.284
		3	3.210	5.384	.552	-7.479	13.899
		4	-.992	5.384	.854	-11.681	9.697
		5	-4.996	5.384	.356	-15.685	5.693

	3	1	-.615	5.384	.909	-11.304	10.074
		2	-3.210	5.384	.552	-13.899	7.479
		4	-4.202	5.384	.437	-14.891	6.487
		5	-8.206	5.384	.131	-18.895	2.482
	4	1	3.587	5.384	.507	-7.102	14.276
		2	.992	5.384	.854	-9.697	11.681
		3	4.202	5.384	.437	-6.487	14.891
		5	-4.004	5.384	.459	-14.693	6.685
	5	1	7.591	5.384	.162	-3.097	18.280
		2	4.996	5.384	.356	-5.693	15.685
		3	8.206	5.384	.131	-2.482	18.895
		4	4.004	5.384	.459	-6.685	14.693
RMSSD	1	2	-2.052	3.359	.543	-8.719	4.616
		3	-1.050	3.359	.755	-7.717	5.618
		4	-2.543	3.359	.451	-9.210	4.125
		5	-2.931	3.359	.385	-9.598	3.737
	2	1	2.052	3.359	.543	-4.616	8.719
		3	1.002	3.359	.766	-5.666	7.670
		4	-.491	3.359	.884	-7.159	6.177
		5	-.879	3.359	.794	-7.547	5.789
	3	1	1.050	3.359	.755	-5.618	7.717
		2	-1.002	3.359	.766	-7.670	5.666

		4	-1.493	3.359	.658	-8.161	5.174
		5	-1.881	3.359	.577	-8.549	4.786
	4	1	2.543	3.359	.451	-4.125	9.210
		2	.491	3.359	.884	-6.177	7.159
		3	1.493	3.359	.658	-5.174	8.161
		5	-.388	3.359	.908	-7.056	6.280
	5	1	2.931	3.359	.385	-3.737	9.598
		2	.879	3.359	.794	-5.789	7.547
		3	1.881	3.359	.577	-4.786	8.549
		4	.388	3.359	.908	-6.280	7.056
pnn50	1	2	-1.371	2.239	.542	-5.816	3.075
		3	-.933	2.239	.678	-5.379	3.512
		4	-.312	2.239	.889	-4.757	4.134
		5	-.535	2.239	.812	-4.980	3.911
	2	1	1.371	2.239	.542	-3.075	5.816
		3	.437	2.239	.846	-4.008	4.883
		4	1.059	2.239	.637	-3.387	5.504
		5	.836	2.239	.710	-3.610	5.281
	3	1	.933	2.239	.678	-3.512	5.379
		2	-.437	2.239	.846	-4.883	4.008
		4	.621	2.239	.782	-3.824	5.067
		5	.399	2.239	.859	-4.047	4.844

	4	1	.312	2.239	.889	-4.134	4.757
		2	-1.059	2.239	.637	-5.504	3.387
		3	-.621	2.239	.782	-5.067	3.824
		5	-.223	2.239	.921	-4.668	4.223
	5	1	.535	2.239	.812	-3.911	4.980
		2	-.836	2.239	.710	-5.281	3.610
		3	-.399	2.239	.859	-4.844	4.047
		4	.223	2.239	.921	-4.223	4.668
LF%	1	2	-.042	.042	.320	-.125	.041
		3	-.055	.042	.189	-.139	.028
		4	-.082	.042	.052	-.165	.001
		5	-.012	.042	.768	-.096	.071
	2	1	.042	.042	.320	-.041	.125
		3	-.014	.042	.748	-.097	.070
		4	-.040	.042	.337	-.124	.043
		5	.029	.042	.484	-.054	.113
	3	1	.055	.042	.189	-.028	.139
		2	.014	.042	.748	-.070	.097
		4	-.027	.042	.523	-.110	.056
		5	.043	.042	.308	-.040	.126
	4	1	.082	.042	.052	-.001	.165
		2	.040	.042	.337	-.043	.124

		3	.027	.042	.523	-.056	.110
		5	.070	.042	.099	-.013	.153
	5	1	.012	.042	.768	-.071	.096
		2	-.029	.042	.484	-.113	.054
		3	-.043	.042	.308	-.126	.040
		4	-.070	.042	.099	-.153	.013
HF%	1	2	.007	.033	.837	-.059	.073
		3	.001	.033	.967	-.065	.068
		4	.023	.033	.489	-.043	.089
		5	-.007	.033	.823	-.074	.059
	2	1	-.007	.033	.837	-.073	.059
		3	-.005	.033	.870	-.072	.061
		4	.016	.033	.626	-.050	.083
		5	-.014	.033	.668	-.081	.052
	3	1	-.001	.033	.967	-.068	.065
		2	.005	.033	.870	-.061	.072
		4	.022	.033	.515	-.044	.088
		5	-.009	.033	.791	-.075	.057
	4	1	-.023	.033	.489	-.089	.043
		2	-.016	.033	.626	-.083	.050
		3	-.022	.033	.515	-.088	.044
		5	-.031	.033	.360	-.097	.036

	5	1	.007	.033	.823	-.059	.074
		2	.014	.033	.668	-.052	.081
		3	.009	.033	.791	-.057	.075
		4	.031	.033	.360	-.036	.097
IF%	1	2	-.032	.020	.103	-.071	.007
		3	-.040*	.020	.045	-.079	-.001
		4	-.044*	.020	.028	-.083	-.005
		5	-.022	.020	.259	-.061	.017
	2	1	.032	.020	.103	-.007	.071
		3	-.007	.020	.703	-.046	.031
		4	-.011	.020	.561	-.050	.027
		5	.010	.020	.610	-.029	.049
	3	1	.040*	.020	.045	.001	.079
		2	.007	.020	.703	-.031	.046
		4	-.004	.020	.841	-.043	.035
		5	.018	.020	.374	-.021	.056
	4	1	.044*	.020	.028	.005	.083
		2	.011	.020	.561	-.027	.050
		3	.004	.020	.841	-.035	.043
		5	.021	.020	.276	-.017	.060
	5	1	.022	.020	.259	-.017	.061
		2	-.010	.020	.610	-.049	.029

3	-.018	.020	.374	-.056	.021
4	-.021	.020	.276	-.060	.017

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

When examining the relationship in HRV parameters according to the levels of VR experience, pairwise comparison levels tests were examined. For the LF% value, the 1st level has a significant effect on the 3rd and 4th levels (with more difficult cognitive tasks). Similarly, it is observed that level 3 has a significant difference from level 1, which includes simpler tasks. The more difficult level 4 VR experience has a significant effect on the LF% value at level 1. In conclusion, when all values were analyzed, no significant relationship was found between different difficulty levels of VR experience and HRV parameters.

In this table, where the groups in the study were evaluated together with HRV parameters according to VR experience levels, it is observed that the groups did not differ according to the levels.

Table 8. The effect of group and VR experience levels on the dependent variable

Groups * Level

					95% Confidence Interval	
Dependent Variable	Groups	Level	Mean	Std. Error	Lower Bound	Upper Bound
HRV_mean	0	1	90.750	4.063	82.684	98.816
		2	90.083	4.063	82.017	98.149
		3	90.917	4.063	82.851	98.983
		4	89.917	4.063	81.851	97.983
		5	90.667	4.063	82.601	98.733
	1	1	77.667	4.691	68.353	86.980
		2	76.667	4.691	67.353	85.980
		3	76.889	4.691	67.575	86.203

		4	76.111	4.691	66.797	85.425
		5	76.889	4.691	67.575	86.203
HRV_min	0	1	79.083	3.573	71.989	86.178
		2	79.417	3.573	72.322	86.511
		3	79.917	3.573	72.822	87.011
		4	76.333	3.573	69.239	83.428
		5	76.917	3.573	69.822	84.011
	1	1	65.333	4.126	57.142	73.525
		2	64.778	4.126	56.586	72.970
		3	64.222	4.126	56.030	72.414
		4	62.333	4.126	54.142	70.525
		5	60.444	4.126	52.253	68.636
HRV_max	0	1	100.500	4.402	91.760	109.240
		2	99.417	4.402	90.677	108.156
		3	101.333	4.402	92.594	110.073
		4	100.333	4.402	91.594	109.073
		5	101.667	4.402	92.927	110.406
	1	1	90.222	5.083	80.130	100.314
		2	88.333	5.083	78.242	98.425
		3	88.667	5.083	78.575	98.758
		4	88.444	5.083	78.353	98.536
		5	91.444	5.083	81.353	101.536

SDNN	0	1	34.350	4.985	24.454	44.246
		2	35.740	4.985	25.844	45.635
		3	34.371	4.985	24.475	44.266
		4	41.178	4.985	31.282	51.074
		5	40.110	4.985	30.214	50.005
	1	1	57.096	5.756	45.670	68.523
		2	60.897	5.756	49.470	72.324
		3	55.846	5.756	44.419	67.272
		4	57.442	5.756	46.016	68.869
		5	66.519	5.756	55.092	77.946
RMSSD	0	1	15.187	3.109	9.014	21.360
		2	15.950	3.109	9.777	22.123
		3	14.590	3.109	8.417	20.763
		4	17.329	3.109	11.156	23.502
		5	16.774	3.109	10.601	22.947
	1	1	29.965	3.590	22.837	37.093
		2	33.305	3.590	26.177	40.433
		3	32.662	3.590	25.534	39.790
		4	32.908	3.590	25.780	40.036
		5	34.240	3.590	27.112	41.368
pnn50	0	1	1.209	2.073	-2.907	5.324
		2	1.297	2.073	-2.819	5.412

		3	1.035	2.073	-3.081	5.150
		4	1.642	2.073	-2.474	5.758
		5	1.802	2.073	-2.313	5.918
	1	1	10.361	2.394	5.609	15.114
		2	13.015	2.394	8.262	17.767
		3	12.402	2.394	7.650	17.155
		4	10.552	2.394	5.800	15.305
		5	10.837	2.394	6.085	15.590
LF%	0	1	.701	.039	.624	.778
		2	.734	.039	.657	.811
		3	.699	.039	.622	.776
		4	.774	.039	.697	.851
		5	.687	.039	.610	.764
	1	1	.635	.045	.547	.724
		2	.686	.045	.597	.775
		3	.748	.045	.660	.837
		4	.727	.045	.638	.816
		5	.674	.045	.585	.763
HF%	0	1	.182	.031	.121	.244
		2	.147	.031	.085	.208
		3	.161	.031	.100	.223
		4	.125	.031	.064	.186

		5	.176	.031	.115	.238
	1	1	.151	.036	.080	.222
		2	.173	.036	.102	.244
		3	.169	.036	.098	.240
		4	.162	.036	.091	.232
		5	.172	.036	.101	.242
IF%	0	1	.155	.018	.119	.191
		2	.171	.018	.135	.207
		3	.167	.018	.131	.203
		4	.149	.018	.113	.185
		5	.152	.018	.116	.188
	1	1	.103	.021	.061	.145
		2	.152	.021	.111	.194
		3	.171	.021	.129	.213
		4	.197	.021	.155	.239
		5	.151	.021	.109	.192

The study's results can be summarized into three main points:

1. HRV parameters show no significant differences between different cognitive load levels.
2. Significant differences exist between different groups, with athletes (group 1) generally scoring better in HRV parameters except for HF%, LF%, and IF%.
3. There's a small, non-significant trend towards higher vagally mediated HRV parameters (SDNN & RMSSD) at higher cognitive load levels in both groups, indicating increased parasympathetic activity.

4. Discussion

The data show that the HRV parameters do not differ significantly across the different levels but across groups with group 1 (athletes) having significantly better HRV parameters except for LF%, HF&, IF%.

The preliminary findings, consistent with previous research on HRV in athletes and nonathletes (Aubert, Seps & Becker, 2003), indicate higher HRV parameters among athletes, except for frequency domain measures, along with lower heart rates. This is attributed to athletes' regular exercise leading to physiological adaptations, such as hemodynamic changes (Aubert et al., 2003; Buchheit, 2014). The lack of differences in frequency domain parameters aligns with previous studies (e.g., Da Silva et al., 2014).

Contrary to previous findings, the study didn't find significant differences in HRV parameters related to cognitive load, as seen in previous research (Durantin et al., 2014; Fuentes-Garcia et al., 2019). Interestingly, a non-significant trend toward higher vagally mediated HRV parameters (SDNN, RMSSD), indicating increased parasympathetic activity, was observed in higher cognitive load levels in both groups, somewhat contradicting prior research.

5. Conclusion

This study is a preliminary study that tries to explain whether HRV values are affected by individuals' cognitive performance. In addition, this study was conducted on two different participant groups consisting of athlete and control groups. The mental workload of the participants was applied with a VR-based assessment system and a gradual increase in mental load was realized. In this way, the effect of different cognitive challenge tasks on HRV change according to the participant group was examined. In the results of the study, HRV mean, HRVmin, HRV max, SDNN, RMSSD, and pnn50 parameters were evaluated in the time domain of HRV, while LF%, HF%, and LF/HF% values were studied in the frequency domain.

Similar findings to our study were reported by Hilgarter et al. (2021), who investigated HRV levels in relation to cognitive performance under various stress conditions. They found that higher cognitive performance correlated with higher phasic HRV, independently of demographic factors. Analyzing our results (**Table 7**), we observed significant relationships between different difficulty levels, particularly in LF/HF ratio. Scores from progressively difficult tasks affected each other, indicating a significant impact on cognitive load across levels 1 to 5.

According to the statistical results of the study, HRV parameters did not show a significant difference according to different cognitive difficulty levels. In addition, although HRV parameters showed significant differences between groups, it was observed that participants in the athlete group had better scores in all HRV parameters except HF%, LF%, IF% ($p<0.05$; **Table 5**).

This study pioneers a new field by introducing a VR-based cognitive performance measurement system, allowing evaluation of multiple parameters reflecting working memory efficiency alongside electrophysiological findings. It also uniquely involves elite athletes and senior managers, offering insights into highly qualified individuals. This innovative VR application sets a precedent for future studies in the field.

ACKNOWLEDGEMENTS

We would like to thank Neo Auvra Digital Health and Bionic Technologies Inc. for providing the necessary research environment for conducting this study.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest.

AUTHOR STATEMENT

All necessary declarations regarding ethical approval, consent to participate, consent for publication, availability of data and materials, and code availability have been provided in this study.

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