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Is heart rate variability a predictor for neurofeedback effects?

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Abstract

The goal of this study was to investigate the relationship between heart rate variability (HRV) and performance in a clinical application for brain-computer interfaces, namely Neurofeedback training (NFT) for children with autism spectrum disorder (ASD). HRV parameters in an initial pre-training test predicted performance as well as performance improvements in social cognition following NFT, confirming a relationship between the autonomic nervous system and social cognition. Furthermore, HRV improved after each NFT session in comparison to pre-session levels. However, no direct relationship between resting HRV and NFT performance was found. The decrease in HRV over sessions might be explained by an increase in mental effort due to an increase in difficulty of the NFT protocol. Nonetheless, HRV can serve as a predictor for NFT effects on social dysfunction in autism and HRV-biofeedback might lead to further improvements in social cognition for autistic children.

1 Introduction

Recent studies have suggested that heart rate and its variability (HRV) can be used as predictor for mental effort in a brain-computer interface (BCI) (Pfurtscheller et al. 2013) and can predict P300-based BCI performance (Kaufmann et al. 2012). Additionally, a positive relation between HRV and social cognition was recently shown in able-bodied individuals using the ‘Reading the Mind in the Eyes-test’ (RMET; Baron-Cohen et al. 2001; Quintana et al. 2012). These links between brain and body could be especially important for clinical applications of BCIs such as Neurofeedback training (NFT) for social dysfunction in children with autism spectrum disorder (ASD).

In this study, an EEG-based NFT for children with ASD was implemented as in previous work (Pineda et al. 2008, 2014). ASD is characterized with deficits in social and communicative skills such as imitation and empathy. Besides neurophysiological abnormalities, deficits in the social engagement system have been linked to the regulation of heart rate (Porges 2007). The goal of this study was to investigate if the reported positive relation between HRV and social cognition as well as BCI performance can be replicated in children with ASD. Therefore, (1) resting HRV was correlated with performance in the RMET which was used as an indicator for social cognition and NFT success and (2) HRV in a resting baseline before and after each NFT session was correlated to NFT performance.

2 Methods

Thirteen children (aged 6-17, one female) with a confirmed diagnosis of ASD participated in a pre- and posttest and in sixteen 1-hour NFT sessions twice a week. During the NFT sessions, EEG

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was recorded from one electrode over the right sensorimotor cortex (C4), sampled at 256 Hz and filtered for mu (8-12 Hz), theta (3-8 Hz) and high beta (18-30 Hz) frequency bands. Before and after each NFT session, a 5-min baseline was recorded for HRV analyses (see last paragraph of methods). The children were trained to control a video game involving social interactions by modulation of their mu frequency band. They were not provided with specific control strategies but learned by operant conditioning via feedback. The beta and theta frequency bands inhibited positive feedback in the game if the amplitudes in these frequencies exceeded a certain threshold. The thresholds for mu, beta and theta were set as a function of an initial preceding resting period of baseline activity. The amplitude value for mu was set in the first session and then shaped to get higher in the following sessions. In contrast, the amplitude values of theta and beta were shaped to get lower in the subsequent sessions.

Performance during the NFT was calculated as: $Performance = Hitrate \times Difficulty$ (1)

A hit was defined as fulfilling all threshold criteria (e.g. above mu and below beta and theta) and thus triggering positive feedback in the game. In order to make different parts of the game comparable, the hitrate was defined as: $Hitrate = \frac{Hits}{Minutes}$ (2)

Due to the continuous shaping of the threshold, the possibility of fulfilling all threshold criteria decreased and thus difficulty increased over sessions. In order to adjust the hitrate for the level of difficulty, the distances (Δobs) between the shaped threshold and the preceding baseline were considered. Distances were calculated so that positive numbers reflected the threshold being set easier than the baseline values and negative numbers reflected the threshold being set more difficult than the baseline values. The observed distances were then normed (Δnorm) to the defined standard distance (Δstd). The standard distance was set in a way that the mu (μ) threshold was 50% lower and the beta (β) and theta (θ) threshold was 50% higher than the preceding baseline value which resulted in a difficulty of 1 for the first session. In order to ensure that a distance of zero and negative distance values still show reasonable results, a logarithmic transformation was used:

$$Difficulty = \frac{1}{10^{\Delta norm}} \qquad \Delta norm = \frac{(\sum_{i=\mu\beta\theta} \Delta obs_i - \sum_{i=\mu\beta\theta} \Delta std_i)}{(\sum_{i=\mu\beta\theta} \Delta std_i)} \qquad (3)$$

In the pre- and posttest, two 6-min baselines with open and closed eyes were recorded before the children completed the RMET. In this test, pictures of individuals' eye regions were shown. Based on the eyes, children had either to determine what the individual is thinking or feeling out of 4 possible choices presented at the four corners of the display, or what gender (male or female) the individual is. The percentage of correct responses (Corr%), as well as the reaction time (RT), was calculated.

The electrocardiogram (ECG) was recorded at a sampling rate of 2048 Hz from electrodes attached to the left wrist and the right side of the neck. HRV parameters were analyzed in all 5-min resting baselines before and after each NFT session as well as in the pre- and posttest. The ECG data was down-sampled to 512 Hz and the interbeat interval (IBI) detection and artifact correction were made with the software ARTiiFACT (Kaufmann et al. 2011). The statistical parameters for HRV were calculated with KUBIOS (Tarvainen et al. 2014) and included the SDNN in ms (i.e. standard deviation of IBIs) in the time domain and the power (ms^2) and percentage (%) of high- (HF; 0.15-0.4 Hz) and low-frequency (LF; 0.04-0.15 Hz) measures in the frequency domain derived using Fast Fourier Transformation. SDNN and HF have a positive, LF (%) a negative association with HRV.

3 Results

First, the relationship between HRV and the RMET was investigated. A normal distribution was found for all variables. Children had more Corr% in the gender (M=84, SE=5) than in the emotion recognition (M=52, SE=6) task ($F_{1,12}$=74.5, p<.01) confirming the differences in difficulty of the tasks, and more Corr% in the post- (M=70, SE=5) than in the pretest (M=65, SE=6) by trend ($F_{1,12}$=3.9, p<.1) suggesting improvement as a function of training. There were neither significant effects for RT in the RMET nor for HRV parameters between pre- and posttest.

HRV parameters in the resting baseline of the pretest - but not of the posttest - correlated with Corr% and RT in the RMET of the pre- and posttest (Table 1). In order to adjust the correlations for possible influence of age and gender of the participants, partial correlations were calculated. All correlations above r=±.3 were in the expected direction: The higher SDNN and HF, the higher the Corr% and the shorter the RT in the RMET. For the LF-percentage, the opposite occurred.

Second, HRV parameters during the baselines before and after each NFT session were correlated with hitrate, difficulty and performance during each NFT session. However, the correlations failed to show any consistent pattern. Hitrate decreased over sessions ($F_{7,84}$=9.1, p<.01), whereas difficulty and performance increased ($F_{7,84}$=3.7/1.9, p<.05/.1). The parameters SDNN and HF power showed significantly higher HRV in the baselines after than before each NFT session ($F_{1,12}$=44.4/13, p<.01). However, HF (ms^2, %) decreased and LF (%) increased over the training sessions ($F_{7,84}$=2.3-3.4, p<.05).

		Pretest				Posttest			
		Gender		Emotion		Gender		Emotion	
Pretest		Corr%	RT	Corr%	RT	Corr%	RT	Corr%	RT
	SDNN	.49	-.29	**.61***	-.41	.47	-.40	**.66***	-.44
Eyes	HF (ms^2)	.44	-.31	**.57**$^{(*)}$	-.47	.44	-.42	**.61***	-.40
open	HF (%)	.50	.25	.20	-.19	**.68***	-.47	.48	-.40
	LF (%)	**-.55**$^{(*)}$	-.25	-.22	.10	**-.70***	.42	-.40	.40
Eyes	HF (%)	**.63***	-.07	.36	**-.53**$^{(*)}$	**.67***	-.47	**.63***	-.47
closed	LF (%)	**-.62***	.05	-.37	.51	**-.71***	**.54**$^{(*)}$	**-.63***	.51

Table 1: Bivariate partial correlation coefficients controlled for age and gender between parameters of HRV and RMET. The significance level is indicated with the asterisks (* p<.05, $^{(*)}$ p<.1).

4 Discussion and conclusion

First, our results confirm a positive correlation between HRV and the performance in the RMET, which was proposed by Quintana et al. (2012). Moreover, this relationship between the autonomic nervous system and social cognition can be extended to an autistic population of children. As individuals with ASD have deficits in social cognition, the correlations between HRV in the pretest and emotion recognition in the pre- and posttest suggest that training HRV before starting NFT might boost performance in social cognition. Although participants improved in social cognition as a function of the NFT (i.e. more Corr% in the post- compared to the pretest), this improvement was not evident in HRV (i.e. no difference in HRV between pre- and posttest), which should be linked to the social engagement system (Porges 2007). This suggests that while these systems may occasionally function in a connected or coupled way, they are distinct and orthogonal systems.

Second, we could not find consistent correlations between HRV and performance in our NFT, which was controlled by children on the autism spectrum by modulating frequency bands in the EEG. This is in contrast to Kaufmann et al. (2012) who reported that performance in a P300-based BCI

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could be predicted by HRV in able-bodied individuals. In the present study, HRV improved after each NFT session compared to before, which suggests that the NFT-game was successful in inducing stress-free social interactions. However, across training sessions, HRV decreased, whereas performance increased. As the increase in performance was the product of increasing difficulty and decreasing hitrate, we could explain the decrease in HRV as an increase in mental effort (Pfurtscheller et al. 2013; Cowley et al. 2013). Analyzing HRV during game play itself and not only in the baseline before and after each NFT might reveal more consistent correlations with performance parameters.

To conclude, although we could not show consistent correlations between resting HRV and NFT performance, this study extends the idea that HRV is a good predictor for behavioral performance in social cognition in individuals with ASD, and can be used as an indicator of mental effort rather than performance during NFT. Moreover, the results suggest that HRV-biofeedback might improve NFT effects in social cognition for children on the spectrum.

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