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Ecological assessment of heart rate complexity: Differences between high- and low-anxious adolescents

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ABSTRACT

Nonlinear measures can capture the complex structure of the heart beating, and recordings taken while the individual performs daily activities may help to understand the cardiac system's output in natural conditions. As healthy systems are characterized by having highly complex outputs, we hypothesized that the cardiac output from high anxious adolescents should be less complex than the output from their low anxious counterparts. In this study ECG was recorded for two hours in 50 adolescents while they performed regular school activities. Fractal dimension (FD), scaling exponents and multiscale entropy were calculated on the interbeat intervals time series. Both FD and entropy were significantly lower in the high-anxious group than the low-anxious group. These results suggest different heart-related regulation in adolescents who suffered from high anxious symptomatology.

1. Introduction

Anxiety disorders are the most prevalent among young people (Costello et al., 2003; Essau et al., 2000, 2002; Snyder et al., 2009), and in recent years considerable advances have been made in understanding them. However, further knowledge concerning their etiology is still needed (Beidel and Alfano, 2011). Psychobiological theories propose that resting vagal tone may be an important physiological index of emotional dysregulation, which is a characteristic of anxiety problems (Porges, 2007, 2011; Thayer and Lane, 2000). In adult samples anxiety disorders have been found to be accompanied by heart rate variability (HRV) reductions attributed to the parasympathetic system (see Chalmers et al., 2014 for a review). In children and adolescents, the literature points in a similar direction but is less conclusive (see Graziano and Derefinko, 2013 for a review). Findings regarding the association between resting vagal tone and young people's anxiety among non-clinical community samples have been inconsistent across studies, yielding both negative associations (El-Sheikh et al., 2011; Greaves-Lord et al., 2007, 2010; Scott and Weems, 2014) and absence of relationships between resting vagal tone and anxiety/internalyzing symptomatology (El-Sheikh et al., 2001, 2011; El-Sheikh and Whitson, 2006; Wetter and El-Sheikh, 2012). All these studies, however, share two limitations. Firstly, only linear measures, whether in the time domain or in the frequency domain, were calculated on the heart outputs, e.g. instantaneous heart rate (HR) time series or interbeat intervals (IBIs) time series. These measures cannot capture the rich, complex structure of the beating heart (Costa et al., 2008), and nonlinear measures are required to this end. Secondly, ECG recordings were obtained in lab settings over short periods of time (usually 5 min), therefore the ecological validity of these recordings is rather low.

Quantifying the HRV by linear methods is not sufficient to analyze cardiac data because the cardiac system, as well as its signal, is highly complex. Fractality is probably the most well-known index of such complexity (Pittman-Polletta et al., 2013). The self-similar, fractal nature of the human heartbeat was discovered thirty years ago (see the influential article by Goldberger, 1996) although not much research has been carried out to understand the meaning of this fractal feature in psychological anxiety-related fields. Several methods are available to study self-similarity in the cardiac output. Fractal dimension (FD) can be measured by using the algorithm developed by Katz (1988), which has already been used in psychophysiological studies (Balle et al., 2015; Beckers et al., 2005; Boettger et al., 2010; Bornas et al., 2013), and was improved by Castiglioni (2010).

Detrended fluctuation analysis (DFA, Peng et al., 1995) is a scaling analysis method used to estimate long-range temporal correlations of power-law form embedded in non-stationary time series. DFA calculates both short-term $\alpha 1$ (4 to 11 heart beats) and long-term $\alpha 2$ (>11 beats) scaling exponents in heartbeat time series. Beyond the field of cardiovascular diseases, the need to distinguish between these two scaling exponents has proved useful in emotion regulation studies (Bornas et al., 2013), anxiety disorders (Agorastos et al., 2013; Baumert et al., 2008), and aging studies (Beckers et al., 2005).

In addition to self-similarity, the amount of entropy has been found to be informative when analyzing cardiac signals. Entropy refers to the amount of new information the system generates as it evolves over time. A periodically oscillating signal reflects a system that does not

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generate much new information, as its behavior becomes highly predictable after one cycle (the system's entropy is very low). On the other hand, a random-like fluctuating signal may come from a non-predictable system showing high entropy. Sample entropy (SampEn, Richman and Moorman, 2000) was introduced as a measure of complexity and has been used to show, for instance, the association between complexity losses (entropy decreases) and adult anxiety states and disorders (Bornas et al., 2006a,b). To measure entropy at different time scales, Costa et al. (2002) introduced Multiscale Entropy (MSE) analysis. Using this analysis is important because complex systems typically show multiscale variability (Costa et al., 2008), i.e. spatio–temporal patterns over a range of scales.

The second limitation of the studies discussed at the beginning of the introduction, as mentioned above, is that cardiac recordings in previous studies on anxiety and HRV have usually been taken in lab settings, and therefore rather short time series are used to obtain measures of HRV. Longer recordings, taken while participants do everyday tasks, may provide valuable information regarding the nature of the cardiac system in spontaneous conditions, and additional knowledge on the associations between anxiety symptomatology (and associated cognitive processes) and the complex cardiac output. Bornas et al. (2013) examined the links between attentional control (AC, one component of effortful control) and complexity of the everyday life HR time series in a sample of healthy college students, and observed a low complexity of HR output associated with low AC. Effortful control (EC) is a broad regulatory dimension of temperament, which in addition to AC includes the ability to inhibit a dominant response (inhibitory control), and to activate a subdominant response (activation control) while experiencing emotion. Unlike reactive temperamental processes, all three kinds of control rely upon the intentionality of the individual to manage emotions (Evans and Rothbart, 2007; Rothbart and Rueda, 2005), and have been involved jointly with an enhanced cardiac vagal control (Spangler and Friedman, 2015). Since enhanced vagal tone has been often associated with high complexity of the cardiac response, a positive relationship between EC and nonlinear cardiac measures would be expected.

To our knowledge, no previous work has examined everyday life HR complexity measures in adolescents with high and low anxiety symptomatology. Hence, the main purpose of the current study was to find out whether there are differences in nonlinear measures of the heart system's complexity between high- and low-anxious adolescents. Since healthy systems are more complex (and thus more flexible and adaptable to the changing environment) than diseased systems (Guastello, 2004), we hypothesized that adolescents with high anxiety symptomatology would show less HR complexity (fractal dimension, scaling exponents, and entropy) than low-anxious adolescents.

The second aim of this study concerns temperament. The interplay of reactive and regulatory temperamental processes appears to be essential for a better understanding of anxiety disorders (Putnam et al., 2002). More specifically, a combination of high emotionality/negative affectivity (reactive temperament) and low EC (regulative temperament) leads individuals to be more prone to develop anxiety disorders (Lonigan and Phillips, 2001; Rothbart et al., 1995; Rothbart and Rueda, 2005). Sportel et al. (2011) studied the role of high behavioral inhibition system (BIS) sensitivity combined with low AC, as a part of reactive and regulative temperament respectively, in symptoms of anxiety disorders in a sample of non-clinical adolescents. The authors observed that the combination of high BIS sensitivity and low AC was associated with the greatest levels of anxiety, suggesting that adolescents with both high BIS and low AC were at risk of developing an anxiety disorder. Regarding the physiological concomitants of reactive and regulative temperament, the integrative conceptual models developed by Beauchaine (2001) and Nigg (2006) propose a reduced vagal tone associated to high BIS sensitivity and low EC respectively. Some studies have provided evidence in this regard with young people (Balle et al., 2013; Chapman et al., 2010; Sulik et al., 2013). The associations between these temperamental factors and heart rate complexity measures are, however, almost unknown, and hence we studied the predictive role of the combination of high-BIS and low EC on HR complexity outcomes. High BIS and low EC should therefore be associated with decreased HR complexity measures.

2. Method

2.1. Participants

The present study was part of a longitudinal study among young adolescents (Bornas et al., 2014). The sample was composed of 24 high-anxious participants (7 male and 17 female, mean age $M = 12.89$, $SD = .42$; mean body mass index [BMI] = 19.87, $SD = 4.30$) and 26 low-anxious participants (11 male and 15 female, mean age $M = 13.03$, $SD = .60$; mean BMI = 20.04, $SD = 2.74$). Details regarding the recruitment process are shown in Fig. 1. The youths were all Caucasian, from middle socioeconomic backgrounds, and both urban and rural areas. The selection variable was anxiety symptomatology as measured with the Revised Child Anxiety and Depression Scale (RCADS; Chorpita et al., 2000). Participants scoring above the 75th percentile in total anxiety symptomatology (scores ≥ 30) were considered as high-anxious. Those with anxiety scores below the 25th percentile (scores ≤ 22) were assigned to the low-anxious group. Exclusion criteria based on information reported by parents, educational boards or clinical interview were: showing a diagnosis of severe mental retardation; a diagnosis of neurological, developmental, or psychiatric disorder (American Psychiatric Association [APA], 2000); or suffering from any severe cardiovascular or respiratory disease.

The University Bioethics Committee approved all procedures, and participants and their parents/tutors provided written consent.

2.2. Psychological measures

2.2.1. Anxiety symptomatology

The RCADS (Chorpita et al., 2000) was used to assess anxiety symptoms. It is a 47-item self-report questionnaire, with scales corresponding to separation anxiety disorder, social phobia, generalized anxiety disorder, panic disorder, obsessive compulsive disorder, and major depressive disorder. There is an overall scale indicating the total level of anxiety symptomatology. For the purpose of the current study, only this overall scale was used. The RCADS requires respondents to rate how often each item applies to them. Items are scored 0–3 corresponding to 'never', 'sometimes', 'often', and 'always'. The internal consistency of overall anxiety scale within this study sample was $\alpha = .93$.

2.2.2. BIS sensitivity

The Sensitivity to Punishment scale of the SPSRQ-J (Torrubia et al., 2008) was used as a self-report measure of BIS sensitivity. This is a self-report instrument adapted for children and adolescents from the adult version developed by Torrubia et al. (2001). The SPSRQ-J is a 30-item yes–no questionnaire containing two scales of 15 items each: sensitivity to punishment, and sensitivity to reward. Scores for each scale were obtained by adding up all "yes" answers. In the current study, only the Sensitivity to Punishment scale (Cronbach's $\alpha = .81$) was relevant to the hypothesis and was therefore used in the analyses.

2.2.3. Effortful control

The Early Adolescence Temperament Questionnaire (EATQ-Revised-long form; Ellis and Rothbart, 2001) is a 103-item self-report measure of 13 different domains related to adolescent temperament that comprises four principal factors: Negative Affectivity, Effortful Control, Affiliation, and Surgency. Each item has to be answered on a 5-point Likert scale ranging from 1 = 'almost never true' to 5 = 'almost always true'. Total trait and factor scores can be computed by summing ratings across relevant items (after recoding inversely formulated items). The