Revista de Psicología Clínica con Niños y Adolescentes
Vol. 8 nº. 3- Septiembre 2021 - pp 18-25
doi: 10.21134/rpcna.2021.08.3.2

www.revistapcna.com - ISSN 2340-8340

Revista de Psicología Clínica con Niños y Adolescentes

Diminished complexity of heart rate time series in adolescents facing negative events during everyday life

Xavier Bornas, Neus Zuzama, Aina Fiol-Veny, Josep Roman-Juan, & Maria Balle
University Research Institute of Health Sciences, University of the Balearic Islands, Palma, Spain

Abstract

Physiological systems need to be flexible in order to adapt to a changing environment. Negative events, however, induce flexibility reductions that seem necessary for coping purposes. To date, studies have measured linear variability and entropy in heart output, but none have examined the scaling properties of the cardiac system when individuals deal with stressful everyday events. This study was aimed at testing the hypothesis that the complexity of the cardiac dynamics is diminished when individuals face negative events in real life. Cardiac variability (linear) and complexity (nonlinear), as well as discomfort and effectiveness of event-related emotion regulation (EER) were ecologically examined in $N = 65$ adolescents ($M_{age} = 14.80$ years; $SD_{age} = 0.86$; 55.38% girls). Repeated Measures MANOVAs revealed higher heart rate (HR) and lower cardiac complexity (higher long-term scaling exponent, $p = .029$; lower Fractal Dimension FD, $p = .030$; and lower Sample Entropy, $p = .001$) during EER in comparison with non-emotion regulation conditions (NER). Wilcoxon non-parametric tests revealed higher Hurst exponents ($p = .006$) in EER than in NER. No significant correlations were found between discomfort and cardiac variables although the higher the cardiac entropy in NER conditions, the greater the self-rated effectiveness of EER ($p < .050$). EER processes involved increases in HR as well as scaling and FD changes that might reflect the real-time scale's predominance in HR output when adolescents are dealing with negative events.
Keywords: adolescence; emotion regulation; cardiac complexity; heart rate variability; observational descriptive study.

Resumen

Complejidad reducida de las series temporales de frecuencia cardíaca en adolescentes afrontando eventos negativos diarios. Los sistemas fisiológicos necesitan ser flexibles para adaptarse a un entorno cambiante. Sin embargo, los eventos negativos disminuyen dicha flexibilidad que parece necesaria para lograr un afrontamiento exitoso. Hasta entonces, los estudios han medido la variabilidad lineal y la entropía de la frecuencia cardíaca (FC), pero ninguno ha examinado las propiedades de escala del sistema cardíaco cuando se afrontan acontecimientos estresantes diarios. Este estudio investigó si la complejidad cardíaca disminuye cuando los individuos se enfrentan a eventos negativos cotidianos. La variabilidad cardíaca (lineal) y la complejidad (no lineal), así como el malestar y la eficacia de los episodios de regulación emocional (EER) se examinaron ecológicamente en $N = 65$ adolescentes ($M_{edad} = 14{,}80$; $DE_{edad} = 0{,}86$; 55,38% chicas). Los MANOVA de medidas repetidas revelaron una mayor FC y una menor complejidad cardíaca (mayor exponente de escala a largo plazo, $p = .029$; menor dimensión fractal DF, $p = .030$; y menor entropía muestral, $p = .001$) durante los EER en comparación con las condiciones de no regulación emocional (NER). Las pruebas de Wilcoxon revelaron mayores exponentes de Hurst ($p = .006$) en EER que en NER. No hubo correlaciones significativas entre el malestar y las variables cardíacas, pero a mayor entropía cardíaca en NER, mayor eficacia autocalificada en EER ($p < .050$). Los EER implicaron aumentos en la FC, así como cambios en la escala y en la DF que podrían reflejar el predominio de la escala en tiempo real del sistema cardíaco cuando los adolescentes afrontan eventos negativos.
Palabras clave: adolescencia; regulación emocional; complejidad cardíaca; variabilidad del ritmo cardíaco; estudio observacional descriptivo.

Exposure to acute and chronic stressful events is one of the most significant risk factors for psychopathology (Schönfeld, et al., 2016), especially during adolescence (Geng et al., 2020). Adolescence is a period characterized by continuous changes at the physical, emotional, cognitive, and social levels, and these fluctuations can become a source of stress. Therefore, the ability of adolescents to cope with stressful events and circumstances and also to regulate emotions across situations may play a primary role in reducing the risk of psychopathology (Compas, et al., 2017).

Under everyday living conditions, the body's physiological sys-

Corresponding author:
Neus Zuzama Pons
University Research Institute on Health Sciences (IUNICS), University of the Balearic Islands.
Cra. de Valldemossa, km 7.5, 07122. Palma, Mallorca, Spain.
E.mail: neuszuzama@gmail.com

tems must be flexible in order to continuously adapt to changing environmental demands. Leaving aside the classic theory of homeostasis, which implicitly assumes functioning on just one timescale (the real-time scale, i.e., what happens here and now), the cardiac system behaves in a complex manner (Goldberger, 2002; West, 2006). Operating on different timescales is thought to improve flexibility, since "the lack of a characteristic scale helps prevent excessive mode locking that would restrict the functional responsiveness of the organism" (West, 2006, p.198). Meanwhile, complex systems usually show irregular and unpredictable behaviour, and therefore the entropy calculated on their outputs (e.g., cardiac signals) is rather high, whereas simple systems are predictable and their entropy is low. Entropy measures are among the most used to study the complexity of physiological systems in states of psychological distress in the last few decades (for a review, see De la Torre-Luque, et al., 2016).

When individuals are faced with a negative event (e.g., a fight with peers), their resources must be focused on real-time functioning so as to boost their capacity to cope successfully. Sympathetic activity boosts the heart rate (HR), whereas parasympathetic withdrawal reduces heart rate variability (HRV; Porges, 2003). We might wonder whether changes also occur in the complex structure of cardiac output within which these systems should be considered (Balle, et al., 2015). More specifically, if the real-time scale prevails when dealing with negative events, a reduction in physiological complexity should be expected. It is worth noting that the vast majority of studies that report complexity losses in stressful situations (e.g., Bornas et al., 2006; Fiol-Veny, et al., 2019; Williamon, et al., 2013) measured entropy. As Goldberger, Peng, and Lipsitz (2002) point out, entropy is not a direct index of physiological complexity, and as such does not prove the nonlinear properties of the signal, neither does it quantify fractal scaling behaviour (p. 24). Whereas entropy refers to the time course of the signal, scaling refers to the range of available timescales for the system to operate (including the real-time scale). Therefore, changes in entropy may or may not be associated with changes in scaling. A considerable amount of evidence supports the hypothesis of entropy loss in stressful situations, but evidence on hypothetical scaling reduction in these situations is still very scarce.

Coping processes include those aimed at regulating event-induced emotions, and a failure to regulate emotion or affect is a risk factor for later mental difficulties (Berking & Wupperman, 2012). However, it is not the effectiveness (success or failure) but the emotion regulation process itself that requires the real-time scale to prevail in the functioning of the cardiac system (i.e., temporary loss of complexity).

The purpose of this study was to investigate HR complexity and HRV under ecological conditions in a sample of healthy adolescents during emotion regulation processes triggered by a negative event. The main hypothesis was that HR complexity given by scaling, fractal dimension, and entropy measures when individuals regulate emotions caused by a negative event would be lower than in everyday circumstances with no negative event. Although HR was expected to be higher during the negative event, HRV was expected to be lower than during the non-negative event. This loss of complexity would be independent of the effectiveness of the emotion regulation coping processes. Furthermore, we hypothesized a significant positive association between level of discomfort and HR complexity.

Method

Participants

Adolescents from nine randomly selected high-schools from Palma de Mallorca (Balearic Islands, Spain) were asked to participate in the study. All participants who agreed to participate were middle-class Caucasians. Exclusion criteria were suffering from any diagnosed psychopathological disorder (American Psychiatric Association, 2000) or currently undergoing psychological or psychiatric treatment. As a result, one adolescent presenting Major Depression Disorder and one with Social Anxiety Disorder were excluded. Seven adolescents were also excluded due to incomplete self-report and apparatus failure (n = 9 out of n = 74, 12.16%; see the 'Data Acquisition and Pre-Processing' section). The final sample comprised N = 65 adolescents (*Mage* = 14.80; *SDage* = 0.86; range = 14-17 years old; mean body mass index [BMI] = 22.5; 55.38% girls). The study was approved by the University of the Balearic Islands' Bioethics Committee (code number: 5311), and all participants and their parents/legal guardians provided written consent. Each adolescent was given 50 euros' compensation for taking part in the study.

Instruments

Psychological assessment

The Kiddie-Schedule for Affective Disorders and Schizophrenia, Present and Lifetime Version (K-SADS-PL; Kaufman et al., 1997) is a semi-structured clinical interview designed to identify current and lifetime child psychiatric diagnoses based on the Diagnostic and Statistical Manual of Mental Disorders (American Psychiatric Association, 2000). We used the Spanish version of the interview, developed by Ulloa et al. (2006), which gathers data from both adolescents and their parents. This interview was used to determine whether the adolescents presented any psychiatric disorders. Only participants who were suspected of suffering from a current psychiatric disorder were excluded. The presence of lifetime disorders was also recorded but was not used as an exclusion criterion.

Ecological Momentary Assessment

Using the Clinicovery web tool (https://clinicovery.com), we designed a template for adolescents to report the required data using their smartphones at 12 different time points. Each template consisted of a structured questionnaire, adapted from previous ecological momentary assessment studies (e.g., Tan et al., 2012). The questionnaires, lasting approximately 1 minute, asked the adolescents about the most negative event they had experienced since last filling in a template, even if it was a minor event.

The adolescents were first asked to indicate whether a negative event had happened or whether everything had been fine since they had last answered the questionnaire, via a dichotomized variable (since the last time I registered the questionnaire, there have been some negative events in which I have experienced negative emotions/since I last registered the questionnaire I have felt good). In turn, participants were asked to indicate when the negative event had happened (a few moments ago, about 15 minutes ago, about 30 minutes ago, about 45 minutes ago, 1 hour ago, more than an hour ago – indicate the time – or whether everything had been fine since they had last answered the questionnaire). This information served to retrieve the time series of cardiac activity data.

Considering the questionable quality of the HR recordings obtained by photoplethysmographic devices such as the Fitbit (Benedetto et al., 2018; Georgiou et al., 2018) in situations of high body movement and/or high HR, adolescents were also asked to report if there had been an exceptional situation such as running, climbing stairs, sports activities, etc. in order to avoid distortions in cardiac recordings. In the event that a negative event had occurred, the degree of discomfort triggered by such event was assessed on a scale from 0 to 100 (0 = not at all, 100 = very much).

After indicating the momentary discomfort, adolescents chose which of the following six emotion-regulation strategies (distraction, positive reappraisal, problem solving, acceptance, avoidance, and rumination; see Connor-Smith, et al., 2000) they had used to down-regulate their event-related negative affect (i.e., the discomfort). They could select multiple strategies simultaneously. If none of the strategies fit, they could type their own strategy. Momentary emotion regulation strategies were six dichotomized variables (yes/no) indicating whether an emotion-regulation strategy had been used at each assessment. Examples of items were: “When you were feeling so bad, did you try to get the problem out of your head by doing another activity?” (distraction) and “When you were feeling so bad, did you do anything to try to solve the problem or fix things?” (problem solving).

Finally, participants rated the degree to which they considered that the emotion regulation strategies used had helped them to down-regulate their discomfort (i.e., the effectiveness of the emotion regulation coping process), on a scale from 0 to 100 (0 = not at all, 100 = very much).

Cardiac Records

Adolescents’ cardiac response was recorded by using Fitbit Charge 2™ (Fitbit Inc, n.d.), a wristband-type wearable activity tracker. This portable device has a three-axis acceleration sensor, altimeter, vibration motor, and optical HR monitor. The expected sampling rate for these Fitbit devices was 0.20 Hz (i.e., one value, in beats per minute, every five seconds). Despite the low sampling rate, previous and comparable devices to Fitbit Charge 2™ (e.g., Fitbit Charge HR is based on a very similar recording method) have shown relatively high validity in HR estimation (Bai et al., 2018; Thomson et al., 2019).

Cardiac Measures

Heart Rate Variability

Mean HR and Standard Deviation of NN intervals (SDNN) were used as this is the most frequently used measure for long-term recordings (Task Force of the European Society of Cardiology the North American Society of Pacing Electrophysiology, 1996).

Scaling

Scaling exponents α1 and α2. Detrended fluctuation analysis (DFA) is a method designed by Peng, et al. (1995), which allows for the estimate of temporal power-law form correlations embedded in interbeat interval (IBI) time series. Two scaling exponents were obtained: the $\alpha 1$ exponent, which reflects short-term scaling (4-11 beats), and the $\alpha 2$ exponent, which reflects long-term scaling (>11 beats). $\alpha 1 > \alpha 2$ in healthy individuals. For uncorrelated data $\alpha = 0.5$, while $0.5 < \alpha < 1$ indicates persistent long-range power-law correlations.

Scaling exponent h (Hurst). Allometric aggregation (West, 2006) is a method that examines the relationship between the mean and standard deviation of a HR time series at increasing levels of aggregation. For this purpose, the mean and standard deviation of time series of length N ($x1, x2, x3, \ldots, x_n$) are calculated. Then, each pair of adjacent data points is aggregated ($x1 + x2, x3 + x4, \ldots, x_{n-1} + x_n$) to obtain a time series of length $N/2$, and the mean and standard deviation of that time series are calculated. The prior aggregation process is repeated for 3, 4, 5, and usually up to $N/10$ adjacent data points. Since our IBI time series were quite long – they included a total of 900 values – the aggregation processes were repeated for 1 to 40 adjacent data points. Invariance of this relationship is reflected by a straight line on a log(mean) - log(sd) plot, and the slope of this line is called scaling exponent h (which would be equal to the Hurst exponent if the time series were infinitely long). If fluctuations in the time series are random (as assumed in accordance with homeostatic principles), then $h = 0.5$. If fluctuations are not random but complex (self-similar), then $0.5 > h > 1$.

Fractal Dimension

Higuchi’s Fractal Dimension (HFD; Higuchi, 1988). In order to obtain the fractal dimension of a finite set of observations (time series) , , , ... , a new time-series must be constructed, which is defined as follows:

$$x_k^m = \{x_m, x_{m+k}, x_{m+2k}, x_{m+3k}, \ldots, x_{m+N_m k}\}$$

with $m = 1, 2, 3, \ldots, k$ and $Nm = \mathrm{int}[(N - m)/k]$. For a time interval equal to k, k sets of new time series are obtained (in this study we set $k = 15$). Then the length of the curve associated with each time series is calculated:

$$L_m(k) = \frac{(N-1)}{k^2} \frac{1}{N_m} \sum_{i=1}^{N_m} \left| x_{m+ik} - x_{m+(i-1)k} \right|$$

and the average value is taken:

$$L(k) = \frac{1}{k} \sum_{m=1}^{k} L_m(k)$$

If the average value follows a power law:

$$L(k) \propto k^{-D}$$

then the fractal dimension of the time series is D.

Entropy

SampEn (Richman & Moorman, 2000) is the negative natural logarithm of the conditional probability that two sequences similar for m points remain similar at the next point. SampEn $(m, r, N) = \ln [Am(r)/Bm(r)]$, where $Bm(r)$ is the likelihood that two sequences will match for m points, whereas $Am(r)$ is the likelihood that two sequences will match for $m + 1$ points. Usually, $m = 2$ and tolerance $r = 20\%$ of the standard deviation of the time series of interbeat intervals. High values of SampEn indicate high irregularity and complexity in the signal, whereas lower values imply higher regularity and predictability.

Scaling factor h and HFD were calculated with our own code, which is embedded in an R graphical interface for nonlinear analysis (available upon request). The other measures, HRV (i.e., mean HR and SDNN), DFA derived exponents, and SampEn were calculated using Kubios HRV Software, version 2.1 (Tarvainen, et al., 2014).

Procedure

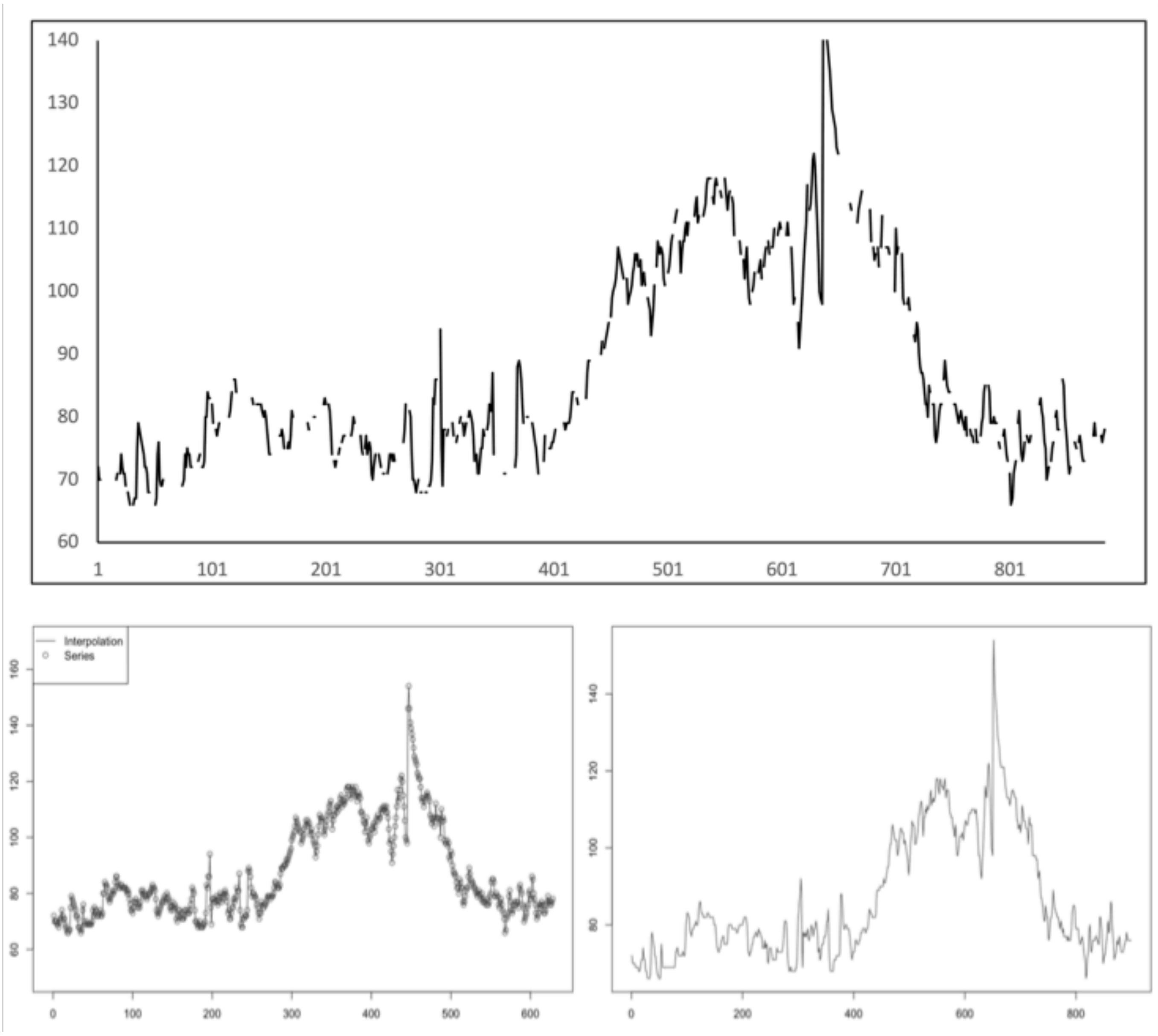
Parents/legal guardians accompanied participants to the university laboratory. In order to detect current adolescent psychopathological disorders, trained evaluators conducted a semi-structured interview (K-SADS-PL) with each adolescent and their parents/legal guardians.

The evaluators then held a psycho-educational session to describe in non-technical terms the main emotion regulation strategies to the participants. During the final section, the app was downloaded from Google Play or Apple Store to familiarize participants with the interview questions. In turn, the researchers provided the participants with a portable Fitbit Charge 2™ device (see description in section 2.4 above) for continuous HR recording purposes. This wearable device was configured to be worn on their non-dominant hand. At the same time, each participant was given an ID and a password for the synchronization of the information during the period of the study. Cardiac data would be rerouted to the Clinicovery App©, which would centralize both the self-reported information from the questionnaire and the momentary HR.

At home and at pre-scheduled times, participants were sent a notification through the Clinicovery App©, asking them to complete an electronic template (see the description in the Measures section). The adolescents were asked to report whether they had experienced negative emotions in response to a self-defined negative event that had occurred since their last completion of an electronic template.

Data were collected over a four-day period from Friday after school through to the following Monday evening, thus covering an equal number of school and rest days (Tan et al., 2012). The adolescents were notified to complete a template twice between 5 p.m. and 10 p.m. on school days (Friday and Monday) and four times between 11 a.m. and 10 p.m. on Saturday and Sunday, amounting to a total of 12 templates. At the end of the 4-day period, participants returned the device to the laboratory.

Figure 1 The upper figure represents the original time series of an adolescent's HR during an EER in which missing values can be observed. The lower figures represent the linear interpolation process (left) carried out to remedy the missing values issue, and the resulting time series (right). The Y-axis represent the HR (beats per minute) and the X-axis represent the number of values of the respective temporal series.



Data acquisition and pre-processing

From each adolescent's 12 templates, two were selected. The first corresponded to the one with the event that generated the highest discomfort and was emotionally regulated (EER). For the second one, a template where they reported not having had to deal with a stressful event (NER) was randomly selected.

In order to analyse the cardiac response related to the occurrence of a negative event, as indicated by Robinson and Clore (2002), a one-hour window is necessary to maximize the possible occurrence of an emotional experience. However, it was decided to extend this by another 15 minutes in case some participants encountered a stressful event just before answering the template. This 15-minute margin enabled us to record the physiological response to the situation, totalling time series of 75 minutes. HR data were exported through the Clinicovery App© according to the time participants had indicated the occurrence of the negative event (i.e., a few moments ago, about 15 minutes ago, about 30 minutes ago, about 45 minutes ago, 1 hour ago, more than an hour ago -indicate the time-; see the 'Ecological Momentary Assessment' section). For example, if a participant at the 8:00 p.m. template indicated the occurrence of a negative event 15 minutes ago (i.e., the stressful event happened at approximately 7:45 p.m.), the HR data was exported from 6:45 p.m. to 8:00 p.m. On the other hand, regarding the time interval selected for daily circumstances without a negative event, the 75 minutes prior to filling in the template were exported. It should be noted that, when the cardiac data were exported, it was verified that none of the selected time intervals coincided with an exceptional situation, such as running or other physical activity, so it was not necessary to rule out any cardiac recordings for this study.

The expected sampling rate for these Fitbit devices was 0.20 Hz (i.e., one value, in beats per minute, every five seconds) but individualized visual examination of HR time series revealed several missing values (adolescents wore the recording devices while performing everyday life activities). Series were therefore linearly interpolated so as to complete them at the sampling rate = 0.20 Hz (see Figure 1).

Finally, the interpolated HR time series were converted to IBIs time series to compute linear and non-linear cardiac measures (see the 'Cardiac Measures' section).

Data analysis

Cardiac variables that violated the normality assumption were *ln* transformed to comply with normal distribution prior to any statistical analysis. Subsequently, two repeated measures (EER, NER) analyses of variance (MANOVAs) were performed – one including linear measures HR and *ln*SDNN, and the other one for nonlinear measures $\alpha 1$, $\alpha 2$, *h*, HFD, and SampEn – to test the complexity loss hypothesis behind this study. Nonparametric tests were used when the distributions of the scores were not normal.

Bivariate Pearson's *r* correlation coefficients (or the Spearman *rho* values when the normality of the distributions could not be assumed) were calculated to evaluate the degree of association between cardiac measures and (a) self-reported discomfort levels in EER conditions, and (b) self-rated effectiveness of the emotion regulation coping process.

Statistical analyses were conducted using IBM SPSS Statistics v.23 package. In order to interpret the effect size of the results, Cohen's (1998) $\eta^2_{partial}$ was used. Based on Cohen's guidelines for labeling the magnitude of effect sizes (Cohen, 1988), $\eta^2_{partial}$ around 0.01 indicates a small effect, an $\eta^2_{partial}$ around 0.06 indicates a medium effect, and an $\eta^2_{partial}$ greater than 0.14 is already a large effect.

Results

In relation to the emotion regulation strategies used by adolescents in EER with the highest discomfort, 50.77% of the overall sample used distraction, 26.15% reappraisal, 7.69% problem-solving, 7.69% acceptance, 1.54% avoidance, and none of the adolescents used rumination. Four participants (75% girls) reported not having used any emotion regulation strategy in facing the negative event.

Descriptive statistics of adolescents' degree of discomfort when facing the negative event and degree of effectiveness in downregulating negative emotions as well as cardiac measures recorded during the study are depicted in Table 1.

Repeated measures MANOVA on cardiac linear measures (HR and *ln*SDNN) showed a significant main effect of condition ($F(2, 63) = 13.897$, $p < .001$). For the overall sample, the cardiac pattern followed an increase in HR ($F(1, 64) = 6.53$, $p = .013$; $\eta^2_{partial} = .093$) and *ln*SDNN ($F(1, 64) = 11.72$, $p = .001$; $\eta^2_{partial} = .155$) from NER to EER, with a medium and large magnitude of the differences effect size between group means, respectively.

Table 1. Mean (SD) of psychological variables during EER and of cardiac variables during EER and NER (n = 65)

	EER	NER
Psychological variables		
Degree of discomfort	49.00 (46.00)	-
Degree of effectiveness	30.20 (26.70)	-
Cardiac variables		
HR	83.14 (13.16)	79.11 (10.21)
*ln*SDNN	4.43 (0.31)	4.25 (0.35)
DFA $\alpha 1$	1.66 (0.11)	1.65 (0.10)
DFA $\alpha 2$	1.32 (0.13)	1.27 (0.13)
h	0.95 (0.04)	0.93 (0.04)
HFD	1.37 (0.06)	1.40 (0.08)
SampEn	0.40 (0.13)	0.48 (0.16)

Note. HR = heart rate; lnSDNN = logarithmic transformation of standard deviation of NN intervals; DFA α1 = alpha 1 exponent calculated by Detrended Fluctuation Analysis; DFA α2 = alpha 2 exponent calculated by Detrended Fluctuation Analysis; h = the scaling exponent h; HFD = fractal dimension, Higuchi method; SampEn = Sample Entropy; EER = emotion regulation event; NER = non-emotion regulation event.

Repeated measures MANOVA on cardiac nonlinear measures ($\alpha 1$, $\alpha 2$, HFD, and SampEn) revealed a significant effect of condition ($F(4, 61) = 3.760$, $p = .008$). No differences were found in DFA $\alpha 1$ ($F(1, 64) = .27$, $p = .604$). By contrast, within-subject effect showed that DFA $\alpha 2$ increased from NER to EER ($F(1, 64) = 4.98$, $p = .029$) with a medium magnitude of the differences effect size between group means ($\eta^2_{partial} = .072$). Additionally, a decrease from NER to EER was found in HFD ($F(1, 64) = 4.90$, $p = .030$; $\eta^2_{partial} = .071$) and in SampEn ($F(1, 64) = 12.58$, $p = .001$; $\eta^2_{partial} = .164$) with a medium and large magnitude of the differences effect size between group means, respectively. Finally, the nonparametric paired *t*-test (Wilcoxon) revealed a decrease in *h* from NER to EER ($W = 649.00$, $p = .006$).

No significant correlations were found between cardiac measures and discomfort during EER events. As to the effectiveness of the emotion regulation process, DFA $\alpha 1$ in NER conditions was significantly and negatively correlated with effectiveness ($r = -.323$, $p < .010$) whereas SampEn in NER conditions positively correlated with effectiveness ($r = .302$, $p < .050$). No significant correlations were found between other cardiac measures and the effectiveness of the emotion regulation.

Discussion

In this study we examined how adolescents deal with daily negative events. These events generate emotion discomfort, and individuals usually display cognitive emotion regulation strategies to successfully alleviate it. Concomitant changes occur in cardiac system dynamics, including HR increases, HRV decreases, and entropy reductions. How the complex nature of cardiac output, and specifically its scaling properties, change in these conditions remains, however, almost unexplored (Fiol-Veny, et al., 2019).

In accordance with a complex systems approach to the functioning of physiological systems, we posed the hypothesis that whereas the lack of a characteristic scale provides the flexibility the system needs to adapt to everyday environmental demands (West, 2006), the real-time operating scale should prevail when individuals face acutely stressful events and regulate their emotions. In other words, we tested the prediction that the complexity (scaling) of the HR time series would be lower when individuals are faced with a negative event in everyday life as opposed to when they are not.

The results clearly support the complexity loss hypothesis since both the Hurst exponent h and HFD revealed lower scaling in cardiac output from EER conditions as compared with NER conditions – the h exponent can be seen as an indirect measure of fractality since $h = 2 - \text{FD}$, and therefore the higher the h exponent, the lower the FD. As for DFA exponents, adolescents showed higher DFA $\alpha 2$ – the long-term scaling exponent – in EER with respect to NER conditions; whereas DFA $\alpha 1$ – the short-term exponent – was not statistically different between both conditions. Interestingly, Fiol-Veny, et al. (2019) reported opposite findings when they induced acute stress in a lab setting, i.e., the short-term exponent dramatically increased under acute stress, but no changes were seen in the long-term exponent. Thus, it is possible to say that acute and time-limited stress (like the short public speech used in that study) alters the short-term scaling of the cardiac system while the long-term fractal structure is preserved. However, moderate stress in everyday life does not alter short-term scaling but requires the long-term structure to be less complex (probably as long as the emotion regulation process takes place). Given that events did not generate much stress in this study (mean discomfort level was 50 in the 0 to 100 scale), the cardiac system did not show a quick, strong reaction but rather a smooth complexity reduction consisting of a lowering of its long-term scaling properties. According to West (2006) scaling reduction can be interpreted as a way to facilitate mode locking, that is to respond here and now to the discomfort generating negative event. In addition, entropy was significantly lower in EER conditions, meaning that heart output was much more regular and predictable when adolescents faced the negative event.

When linear measures were used to compare EER and NER conditions, HR was slightly higher when facing the negative event, as expected. Unexpectedly, *ln*SDNN was higher when adolescents faced the negative event than when they did not. Strictly speaking, SDNN measures the amplitude of IBIs fluctuations around the mean value. The larger the amplitude, the higher the SDNN value. This means that over the 75 minutes of recordings (which included the process of coping with the negative events) adolescents showed large fluctuations in the length of IBIs around a slightly increased HR. These larger fluctuations may be the result of changes in the cognitive-emotion state of the individual throughout the coping process. One individual, for instance, may feel upset at the beginning of the event, followed by a high cognitive load due to attentional processes leading to a more calmed state during several minutes, and so on. It is not surprising that the heart beating of this individual would change several times over the 75 minutes' period, thus showing a high *ln*SDNN value. All these changes occur in the real-time scale (the here and now), i.e., they are locked to the real time emotion and cognitive experience.

The second aim of this study concerned the associations between psychological variables and cardiac complexity. Discomfort was not associated with any cardiac variable, not even with the HR increase in EER conditions, probably because negative events were not strongly stressful. Further, we did analyse rather long HR time series (75 minutes), whereby HR reactivity occurring immediately after the negative event might have gone unnoticed.

Although adolescents had to select which specific strategies they used to cope with the negative events, this information could not be analysed. Thirty-three participants (half of the sample) selected "distraction" in the template, and this was probably due to the fact that "distraction" was the first strategy that appeared on the smartphone screen when adolescents had to fill in the template. Obviously, this was an error when the App was designed and will be corrected in future studies.

Associations were found between the self-rated effectiveness of the coping process and the values of DFA $\alpha 1$ short-term scaling exponent and entropy in NER conditions: lower scaling exponents or higher entropy (both pointing towards high cardiac complexity) in NER conditions were associated with higher ratings of effectiveness. On the other hand, cardiac measures during EER were not associated with the self-rated degree of effectiveness of the emotion regulation strategies. In consequence, losses in cardiac complexity occurred concomitantly with the coping and emotion regulation process, but apparently independently of the outcome of this process. Therefore, although the real-time scale's hypothetical predominance might be a necessity when dealing with a negative event, it does not guarantee a successful outcome.

Limitations and future lines of research

This study has certain limitations that need to be addressed. First, our study might be weakened by the small sample size owing to low participation, the uniformity of our sample in terms of ethnicity and socioeconomic background, with an overrepresentation of middle-class Caucasian adolescents, and the relatively low sampling rate (0.20 Hz) of the Fitbit device used. Regarding the wearable device, it should be noted that the low sampling frequency throw doubt on to the interpretation of "short-term" metrics (SDNN, DFA $\alpha 1$), which are more sensitive to a low sampling rate than "long-term" metrics. These latter better support the low sampling rate. The use of more accurate tools such as a chest strap to measure HR would be preferable, but it would be very uncomfortable for participants to wear an electrocardiographic device for such a long time and would seriously compromise the emotional dimension of the study. Therefore, although these results are promising indicators about the association between cardiac reactivity and emotion regulation during adolescents' everyday lives, statistical validation with larger samples is required. One direction that would also be interesting to address in future research is to determine which fractal scale (e.g., the optimal k_{max} parameter in Higuchi's fractal dimension) best differentiates EER episodes from NER episodes.

Furthermore, as suggested by Tan et al. (2012), the retrospective methodology might lead to response biases, such as a tendency to remember the most recent experiences. Thus, if there have been several negative events since the last time the adolescents answered the questionnaire, they might focus on the most recent one, even though some of the previous ones were more intense and were the ones that really interested us. In this regard, it would be interesting to complement this research with other longitudinal studies.

Another limitation is that we focused on asking about the effectiveness of the emotion regulation strategies used after the negative event, but we should also have asked about the level of discomfort after using them. Without this information it is hard to conclude precisely to what extent their feeling of discomfort was allayed following the implementation of an emotion regulation strategy. Future research should address this issue and change the questions format to avoid distortions in the participants responses. As noted above, the information regarding the specific emotion regulation strategies used by adolescents to cope with negative events could not be analysed in this study, since most of them specified having used *distraction*. The fact that *distraction* was the first strategy that appeared on the smartphone screen when adolescents had to fill in the template probably biased participants' answers.

Finally, the present study compared HR complexity and HRV between emotion regulation conditions and non-emotion regulation conditions in a sample of healthy adolescents. However, future research should try to replicate these findings by using clinical samples of adolescents with internalizing disorders that hinder their coping processes.

Conclusions and Clinical Relevance

The findings obtained in the present study provide a useful contribution to the scientific literature to understand how adolescents regulate their emotions in their everyday life, using the Dynamic Systems Theory as the main theoretical framework. Since emotion regulation is a very complex and multifaceted process entailing evaluative-affective, behavioral, and physiological processes, a complex-system approach is necessary to design prevention and intervention strategies. To our knowledge, this study is the first to examine the scaling properties of HR output during the regulation of emotions elicited by daily negative events, and to provide evidence of cardiac scaling and cardiac entropy reductions associated with emotion regulation processes. Regarding linear measures, as expected, HR was slightly higher when adolescents faced the negative event, but not as a result of vagal withdrawal. Contrary to our hypothesis, adolescents showed large fluctuations in the length of IBIs around a slightly increased HR probably resulting from changes in the cognitive-emotion state throughout the coping process. As for the degree of discomfort experienced during the negative event, this was not associated with any cardiac variable. Moreover, the real-time scale predominance did not guarantee a successful emotion regulation, meanwhile high cardiac complexity in neutral events (i.e., non-negative) was associated with higher successful outcome in emotion coping.

The results presented here are in line with recent studies that point to autonomic nervous system flexibility as a global psychophysiological index of resilience (i.e., the process of achieving positive outcomes despite exposure to significant stressful events; An et al., 2020). The association between low HRV and various psychological disorders (Huang et al., 2018; Kim, et al., 2018) and between high HRV and adaptive responses to stress (Bornstein & Suess, 2000) may suggest that maintaining parasympathetic dominance during no stressful periods may be essential for thriving in the face of adversity. In this study, high cardiac complexity in neutral events has been associated with a higher successful outcome in emotion coping. In this sense, developing adaptive strategies (e.g., reappraisal) targeted to enhance the flexibility of these systems and, therefore, increase resistance (resilience) to stress in the face of repeated daily stressors (Min et al., 2013; Volokhov & Demaree, 2010), could be of interest to promote better physical and mental health in adolescents with emotion regulation difficulties. Furthermore, habituation of biological responses when faced with repeated exposure to similar stressful situations in daily life might be an indicator of resilience in clinical practice (Bennett, et al., 2018). Although it is not possible to remove stress from everyday life, we can boost the development of emotion flexibility, thereby mitigating the long-term effects of stress on health.

Funding

This research was supported by the Spanish Ministry of Economy and Competitiveness (MINECO), the State Research Agency (AEI) and the European Regional Development Funds (ERDF) [grant number PSI2016-78403-P (MINECO/AEI/ERDF, EU)]; by the Service of Occupation of the Balearic Islands (SOIB), the European Social Fund (ESF) and Youth Guarantee from the Spanish Ministry of Employment and Social Security [ref. number SJ-QSP-48/19].

Conflict of interest

The authors declare no conflict of interest.

Acknowledgments

We would like to thank Jordi Penalva Vadell from the Department of Mathematics for his assistance with the interpolation process.

References

American Psychiatric Association (2000). *Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition Text Revision (DSM-IV-TR)*. Washington, DC: American Psychiatric Association.

An, E., Nolty, A. A. T., Amano, S. S., Rizzo, A. A., Buckwalter, J. G., & Rensberger, J. (2020). Heart rate variability as an index of resilience. *Military Medicine, 185*(3-4), 363-369. https://doi.org/10.1093/milmed/usz325

Bai, Y., Hibbing, P., Mantis, C., & Welk, G. J. (2018). Comparative evaluation of heart rate-based monitors: Apple watch vs Fitbit charge HR. *Journal of Sports Sciences, 36*(15), 1734-1741. https://doi.org/10.1080/02640414.2017.1412235

Balle, M., Morillas, A., Tortella-Feliu, M., & Bornas, X. (2015). Heart rate complexity and attentional orienting: A new look at the role of vagal tone. *Nonlinear Dynamics, Psychology, and Life Sciences, 19*(2), 101-110.

Benedetto, S., Caldato, C., Bazzan, E., Greenwood, D. C., Pensabene, V., & Actis, P. (2018). Assessment of the fitbit charge 2 for monitoring heart rate. *PLoS ONE, 13*(2), 1-10. https://doi.org/10.1371/journal.pone.0192691

Bennett, J. M., Rohleder, N., & Sturmberg, J. P. (2018). Biopsychosocial approach to understanding resilience: Stress habituation and where to intervene. *Journal of Evaluation in Clinical Practice, 24*(6), 1339-1346. https://doi.org/10.1111/jep.13052

Berking, M., & Wupperman, P. (2012). Emotion regulation and mental health: Recent findings, current challenges, and future directions. *Current Opinion in Psychiatry, 25*(2), 128-134. https://doi.org/10.1097/YCO.0b013e3283503669.

Bornas, X., Llabrés, J., Noguera, M., López, A. M., Gelabert, J. M., & Vila, I. (2006). Fear induced complexity loss in the electrocardiogram of flight phobics: a multiscale entropy analysis. *Biological psychology*, *73*(3), 272-279. https://doi.org/10.1016/j.biopsycho.2006.05.004

Bornstein, M. H., & Suess, P. E. (2000). Physiological self-regulation and information processing in infancy: Cardiac vagal tone and habituation. *Child Development, 71*(2), 273-287. https://doi.org/10.1111/1467-8624.00143

Clinicovery. (n.d.). https://clinicovery.com

Cohen, J. (1988). Statistical power analysis for the behavioral sciences (2nd edition). Hillsdale, NJ: Erlbaum.

Compas, B. E., Gruhn, M., & Bettis, A. H. (2017). Risk and resilience in child and adolescent psychopathology. In T. P. Beauchaine & S. P. Hinshaw (Eds.), *Child and Adolescent Psychopathology* (3rd ed., pp. 114–143). New York, NY: Wiley.

Connor-Smith, J., Compas, B.E., Wadsworth, M.E., Thomsen, A.H., & Saltzman, H. (2000). Responses to stress in adolescence: Measurement of coping and involuntary stress responses. *Journal of Consulting and Clinical Psychology*, *68*, 976–992. https://doi.org/10.1037//0022-006X.68.6.976

De la Torre-Luque, A., Bornas, X., Balle, M., & Fiol-Veny, A. (2016). Complexity and nonlinear biomarkers in emotional disorders: A meta-analytic study. *Neuroscience and Biobehavioral Reviews, 68*, 410-422. https://doi.org/10.1016/j.neubiorev.2016.05.023

Fiol-Veny, A., Balle, M., De la Torre-Luque, A., & Bornas, X. (2019). Negative cognitive emotion regulation as a predictor of adolescent heart rate variability and entropy under social stress. *Anxiety, Stress, & Coping*, 1-13. https://doi.org/10.1080/10615806.2019.1641199

Fiol-Veny, A., Balle, M., Fiskum, C., & Bornas, X. (2019). Sex differences in adolescents' cardiac reactivity and recovery under acute stress: The importance of nonlinear measures. *Psychophysiology*. https://doi.org/10.1111/psyp.13488

Fitbit Inc. (n.d.). https://www.fitbit.com/es/home

Geng, Y., Gu, J., Zhu, X., Yang, M., Shi, D., Shang, J., & Zhao, F. (2020). Negative emotions and quality of life among adolescents: A moderated mediation model. [Emociones negativas y calidad de vida en adolescentes: un modelo de mediación] *International Journal of Clinical and Health Psychology.* https://doi.org/10.1016/j.ijchp.2020.02.001

Georgiou, K., Larentzakis, A. V., Khamis, N. N., Alsuhaibani, G. I., Alaska, Y. A., & Giallafos, E. J. (2018). Can wearable devices accurately measure heart rate variability? A systematic review. *Folia Medica*, *60*(1), 7-20. https://doi.org/10.2478/folmed-2018-0012

Goldberger, A. L. (2002). Chronic fatigue syndrome and hidden happenings of the heartbeat. *Clinical Autonomic Research*, *12*(4), 228-230. https://doi.org/10.1007/s10286-002-0054-6

Goldberger, A. L., Peng, C. K., & Lipsitz, L. A. (2002). What is physiologic complexity and how does it change with aging and disease? *Neurobiology of aging*, *23*(1), 23-26. https://doi.org/10.1016/S0197-4580(01)00266-4

Higuchi, T. (1988). Approach to an irregular time series on the basis of the fractal theory. *Physica D: Nonlinear Phenomena*, *31*(2), 277-283. https://doi.org/10.1016/0167-2789(88)90081-4

Huang, M., Shah, A., Su, S., Goldberg, J., Lampert, R.J., Levantsevych, O.M., Shallenberger, L., Pimple, P., Bremner, J.D., Vaccarino, V. (2018). Association of depressive symptoms and heart rate variability in vietnam war-era twins: A longitudinal twin difference study. *JAMA Psychiatry, 75*(7), 705-712. https://doi.org/10.1001/jamapsychiatry.2018.0747

Kaufman, J., Birmaher, B., Brent, D., Rao, U., Flynn, C., Moreci, P., Williamson, D., & Ryan, N. (1997). Schedule for affective disorders and schizophrenia for school-aged children —Present and lifetime (K-SADS-PL): Initial reliability and validity data. *Journal of the American Academy of Child and Adolescent Psychiatry, 36*, 980–988. https://doi.org/10.1097/00004583-199707000-00021

Kim, H. G., Cheon, E. J., Bai, D. S., Lee, Y. H., & Koo, B. H. (2018). Stress and heart rate variability: A meta-analysis and review of the literature. *Psychiatry Investigation, 15*(3), 235-245. https://doi.org/10.30773/pi.2017.08.17

Min, J. A., Jung, Y. E., Kim, D. J., Yim, H. W., Kim, J. J., Kim, T. S., Lee, C. U., Lee, C., & Chae, J. H. (2013). Characteristics associated with low resilience in patients with depression and/or anxiety disorders. *Quality of Life Research*, *22*(2), 231-241. https://doi.org/10.1007/s11136-012-0153-3

Peng, C. K., Havlin, S., Stanley, H. E., & Goldberger, A. L. (1995). Quantification of scaling exponents and crossover phenomena in nonstationary heartbeat time series. *Chaos: an interdisciplinary journal of nonlinear science, 5*(1), 82-87. https://doi.org/10.1063/1.166141

Porges, S. W. (2003). The polyvagal theory: Phylogenetic contributions to social behavior. *Physiology & behavior*, *79*(3), 503-513. https://doi.org/10.1016/s0031-9384(03)00156-2

Richman, J. S., & Moorman, J. R. (2000). Physiological time-series analysis using approximate and sample entropy. *American Journal of Physiology - Heart and Circulatory Physiology, 278*(6 47-6), H2039-H2049.

Robinson, M.D., & Clore, G.L. (2002). Episodic and semantic knowledge in emotional self-report: Evidence for two judgment processes. *Journal of Personality and Social Psychology, 83,* 198–215. https://doi.org/10.1037//0022-3514.83.1.198

Schönfeld, P., Brailovskaia, J., Bieda, A., Zhang, X. C., & Margraf, J. (2016). The effects of daily stress on positive and negative mental health: Mediation through self-efficacy. *International Journal of Clinical and Health Psychology, 16*(1), 1-10. https://doi.org/10.1016/j.ijchp.2015.08.005

Tan, P.Z., Forbes, E.E., Dahl, R.E., Ryan, N.D., Siegle, G.J., Ladouceur, C.D., & Silk, J.S. (2012). Emotional reactivity and regulation in anxious and nonanxious youth: a cell-phone ecological momentary assessment study. *Journal of Child Psychology and Psychiatry, 53,* 197-206. https://doi.org/10.1111/j.1469-7610.2011.02469.x

Tarvainen, M. P., Niskanen, J. -., Lipponen, J. A., Ranta-aho, P. O., & Karjalainen, P. A. (2014). Kubios HRV - heart rate variability analysis software. *Computer Methods and Programs in Biomedicine, 113*(1), 210-220. https://doi.org/10.1016/j.cmpb.2013.07.024

Task Force of the European Society of Cardiology. (1996). Heart rate variability: standards of measurement, physiological interpretation and clinical use. Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology. *Circulation*, *93*, 1043-1065.

Thomson, E. A., Nuss, K., Comstock, A., Reinwald, S., Blake, S., Pimentel, R. E., Tracy, B. L., Li, K. (2019). Heart rate measures from the apple watch, fitbit charge HR 2, and electrocardiogram across different exercise intensities. *Journal of Sports Sciences, 37*(12), 1411-1419. https://doi.org/10.1080/02640414.2018.1560644

Ulloa, R. E., Ortiz, S., Higuera, F., Nogales, I., Fresán, A., Apiquian, R., Cortés, J., Arechavaleta, B., Foulliux, C., Martínez, P., Hernández, L., Domínguez, E., & De la Peña, F. (2006). Interrater reliability of the spanish version of schedule for affective disorders and schizophrenia for school-age children-present and lifetime version (K-SADS-PL). *Actas Espanolas De Psiquiatria, 34*(1), 36-40.

Volokhov, R. N., & Demaree, H. A. (2010). Spontaneous emotion regulation to positive and negative stimuli. *Brain and Cognition, 73*(1), 1-6. https://doi.org/10.1016/j.bandc.2009.10.015

West, B.J. (2006). *Where Medicine Went Wrong: Rediscovering the Path to Complexity*. World Scientific Publishing.

Williamon, A., Aufegger, L., Wasley, D., Looney, D., & Mandic, D. P. (2013). Complexity of physiological responses decreases in high-stress musical performance. *Journal of The Royal Society Interface*, *10*(89), 20130719. https://doi.org/10.1098/rsif.2013.0719