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Anxiety, attention, and decision making: The moderating role of heart rate variability

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A B S T R A C T

The current exploratory research examined whether high frequency heart rate variability (HF-HRV) modulates the association between anxiety and (1) executive attentional control during situations involving neutral stimuli, in which the distractor stimuli are in conflict with the target stimulus, and (2) risk aversion in decision making. Forty-five participants (21 with low and 24 with high trait-anxiety) performed a modified version of the Attention Network Test to measure attentional control, and the Balloon Analog Risk Task to measure risk aversion. HF-HRV was recorded during a rest period before completion of the tasks. Results showed that individuals with high anxiety and low HF-HRV have worse attentional control in the face of conflicting information as well as greater risk aversion, in comparison with individuals with both high anxiety and high HF-HRV or low anxiety (regardless of HF-HRV). HF-HRV was positively associated with attentional control and negatively associated with risk aversion. Furthermore, a strong negative association was observed between attentional control and risk aversion. These results suggest that HF-HRV modulates the influence of anxiety on both attentional control to neutral stimuli, and risk aversion in decision making. Greater HF-HRV appears to fulfill a protective role in highly anxious individuals. The associations observed also suggest that executive control of attention plays a relevant role in decision making. These results support the relevance of the autonomic nervous system in sustained cognition and are in accordance with theories in which vagal-mediated heart rate variability is taken as an indicator of prefrontal cortex inhibitory influences.

1. Introduction

Individuals with high anxiety focus their attention preferentially on negative information (MacLeod and Mathews, 1988; Mogg and Bradley, 1999), and have greater difficulty than individuals with low anxiety in disengaging attention from threatening information (see Fox et al., 2005, for a review). Several studies have emphasized the role of attentional control functions in anxiety, referred to the voluntary control exercised by the anterior attention network in situations that require the resolution of stimulus or responses to conflicts (Posner and Dehaene, 1994). Biases to potentially threatening stimuli are associated with alterations in attention control capacity (Eysenck et al., 2007). The advantage of quickly detecting hazards and responding effectively to them can become a disadvantage for anxious people, given that they activate their alert mechanisms in the face of ambiguous or negative information that is irrelevant to most individuals. This negatively affects their performance in various tasks. Moreover, recent studies also suggest a lower attentional control in highly anxious individuals with respect to the processing of non-threatening stimuli (Pacheco-Unguetti et al., 2009, 2010; Ortega et al., 2012).

Attentional control capacity can be viewed as an effortful self-regulatory dimension (Derryberry and Reed, 2002). Effortful control constrains overly reactive emotions and plays a significant role in disengaging from threatening cues and engaging with safety ones (Park et al., 2012). According to Derryberry and Reed (2002), anxious individuals with poor effortful control exhibited attentional biases favoring threatening stimuli, whereas anxious individuals with good effortful control were capable of shifting their attention away from threatening stimuli and engaging with safety stimuli. Lonigan and Vasey (2009) also found an interaction between negative affectivity and effortful control on attentional biases favoring negative information in children. Therefore, an individual's ability to regulate the location of attention can modulate the extent to which attention is directed to either threatening (Cisler and Koster, 2010; Peers and Lawrence, 2009), or non-threatening stimuli (Ortega et al., 2012; Pacheco-Unguetti et al., 2010).

One promising physiological correlate of attentional control is heart rate variability (HRV), an index of autonomic control of the heart that is related to cardiovascular and emotional disorders (Gillie and Thayer,

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2014; Gorman and Sloan, 2000; Pittig et al., 2013). HRV reflects oscillations in the interval (ms) between consecutive heartbeats which result mainly from parasympathetic (vagal) inputs to the heart via the sinoatrial node (Berntson et al., 1997; Reyes del Paso et al., 2013). Vagal cardiac tone has been repeatedly linked to attentional and emotional control (e.g., Duschek et al., 2009, 2013; Hansen et al., 2003; Porges, 1995).

The part of the HRV spectrum more often related to vagal-mediated influences is the high frequency band (HF, from .15 to .40 Hz); the HRV is linked to respiration (i.e., respiratory sinus arrhythmia) (Berntson et al., 1997). Parasympathetic influences are essential for the successful adaptation of the organism to changing environmental demands (Porges, 1995; Reyes del Paso et al., 2009; Thayer and Lane, 2000). Reduction of vagal control (i.e., decreased HF-HRV) could indicate a lack of ability to respond flexibly to changing demands, reducing the range of possible options and thus limiting the ability of individuals to generate appropriate responses and inhibit inappropriate ones.

In accordance with the neuro-visceral integration model (Friedman, 2007; Thayer et al., 2009; Thayer and Lane, 2000) HF-HRV is taken as an index of attentional-emotional regulation that is hypothesized to be related to tonic inhibitory influences from the prefrontal cortex to sub-cortical structures. A low HF-HRV can be interpreted in this context as indicating a dysregulation of this inhibitory network, which can lead to sub-cortical disinhibition with greater arousal and a more rigid and defensive-biased attentional-cognitive pattern (Thayer et al., 2009).

A higher HF-HRV has been linked to more effective strategies for regulating emotion and attention and a faster recovery of the basal state (McEwen, 2000). A lower HF-HRV is associated with worse regulation strategies and the development of mental disorders (Thayer and Brosschot, 2005), especially anxiety (Pittig et al., 2013). According to this hypothesis, individuals with higher HF-HRV (greater vagal control) perform better on executive level, attention span, working memory, processing speed and decision making (Causse et al., 2011; Hansen et al., 2003, 2009; Quintana et al., 2012). At the emotion-regulation level, high HF-HRV is associated with a more flexible and differentiated emotion-modulated startle reflex, while individuals with lower HF-HRV tend to exhibit potentiated startle to neutral and even pleasant foregrounds, indicating aberrances in emotional processing (Ruiz-Padial et al., 2003; Ruiz-Padial and Thayer, 2014). A low HF-HFV predicts the development of post-traumatic stress disorder (PTSD) after a traumatic event, as well as greater symptom severity (Gillie and Thayer, 2014; Shaikh al arab et al., 2012). In adolescents, reduced autonomic flexibility (i.e., lower HF-HRV) predicts levels of anxiety (Greaves-Lord et al., 2010). Park et al. (2013b) found faster attentional engagement to fearful faces in lower vs. higher HF-HRV participants. Miskovic and Schmidt (2010) proved that HF-HRV (in combination with prefrontal electroencephalogram asymmetry) predicted attentional bias to social threats in healthy individuals. Nevertheless, some results do not confirm the neuro-visceral integration model (Britton et al., 2008; Drucaroff et al., 2011; Hovland et al., 2012), and recent studies have shown that there is a need to revise the theory by narrowing and circumscribing its hypothesis, in order to better capture cognitive-visceral interrelations (Jennings et al., 2015).

Some studies suggest that HF-HRV can modulate the relationship between anxiety and attention to fearful and threatening stimuli. In a study performed under flight-like conditions, Bornas et al. (2005) found that anxious individuals with a fear of flying, but with high HF-HRV, directed their attention to the task and reported similar anxiety levels as the non-anxious group. Cocia et al. (2012) also found that HF-HRV moderates the relationship between trait anxiety and disengagement bias to fearful stimuli. High anxiety participants with low HF-HRV showed disengagement bias but this was not observed in anxious participants with high HF-HRV. Melzig et al. (2009) studied the startle response elicited by the threat of receiving an electric shock in people with symptoms of panic disorder and found that those with low HF-HRV had exaggerated startle responses relative to those with high HV-HRV.

Research on the modulatory effect of HF-HRV on cognitive bias to neutral stimuli is scarce. Using fearful and neutral faces as distractors, Park et al. (2013a) found that individuals with low HF-HRV showed difficulties in inhibiting the negative influence of both types of distractors, while in the high HF-HRV group interference was observed only from the fearful faces. In conclusion, individuals with low HF-HRV tended to concentrate more on ambiguous-threatening information, were less able to disengage attention from irrelevant stimuli, failed to recognize safety cues and showed a lower habituation rate to novel and neutral stimuli, displaying a hypervigilance-like state (Thayer et al., 2009).

Taking the above evidence together, it can be postulated that HF-HRV may modulate the relationship between trait anxiety and attentional biases. However, the available evidence about this moderating influence has been gathered using emotionally driven stimuli. To date, no study has used neutral stimuli. Thus, a relevant question that remains poorly studied and deserves further research is whether the moderating influence of HF-HRV on anxiety-related attentional biases could also be observed during tasks using neutral stimuli.

Trait anxiety may influence an individual's ability to make risky decisions. Highly anxious individuals are likely to try to avoid risk (Maner et al., 2007). Several studies describe risk avoidance patterns in anxiety (Mitte, 2007; Miu et al., 2008; Ortega et al., 2012). Because the ability to control and regulate emotions is involved in decision-making, it is relevant to consider whether HF-HRV modulates the effect of anxiety on risk avoidance, as some studies seem to suggest (Fenton-O'Creevi et al., 2012). If low HF-HRV is related to poorer emotional regulation and difficulty in controlling attention, it could be hypothesized that it is also related to higher risk avoidance. Low HF-HRV would increase the impact of anxiety on decision-making, and the conflict between risk-taking and negative assessment by the individual of what could happen, because he/she would focus more on the negative emotions anticipated to result from a poor outcome.

The aim of this study was to analyze the way HF-HRV interacts with trait anxiety to modulate how individuals inhibit distracting information in a conflict situation involving neutral stimuli, as well as their ability to take risks during decision-making. As a secondary objective, we will assess the relationships between attentional control and risk aversion in decision-making. It was hypothesized that: (1) Individuals with high trait anxiety and low HF-HRV will manifest an attentional control bias when the distractor stimuli are in conflict with the target stimulus, compared to those with high trait anxiety but high HF-HRV; (2) Individuals with high trait anxiety and low HF-HRV will exhibit greater risk avoidance than those with high trait anxiety but high HF-HRV; (3) In individuals with low trait anxiety, we hypothesize no differences as a function of HF-HRV either in the appearance of attentional bias or risk avoidance. Furthermore, these individuals would not differ from those with a high trait anxiety and high HF-HRV; and (4) greater attentional control would be associated with lower risk aversion.

2. Method

2.1. Participants

The initial sample of the study included 200 first year Psychology students. Participants were selected and assigned to one of the following two groups according to their trait anxiety scores: the low trait anxiety group (LTA), with scores below 12 (≤percentile 10) on the Trait scale of the State-Trait Anxiety Inventory (STAI-T) (n = 21, 11 females and 10 males), and the high trait anxiety group (HTA), with scores above 28 (≥percentile 80) on STAI-T (n = 24, 14 females and 10 males) (see Table 1). The Beck Depression Inventory (BDI) and the Social Desirability Scale (SDS) (see below) were used like a control

Table 1
Means (M) and standard deviations (SD) of measured variables as a function of trait anxiety group.

	Low anxiety group (n = 21)		High anxiety group (n = 24)		*t*	*p*
	M	SD	M	SD		
Trait anxiety	10.71	4.68	29.08	9.01	−8.40	<.001
Attentional control index	7.83	3.55	16.78	10.42	−3.95	<.001
Risk aversion index	37.05	4.84	19.95	11.12	6.82	<.001
HF-HRV (ln)	5.76	.79	5.59	1.5	.47	.640
Respiratory rate (bpm)	15.17	3.14	15.09	4.02	.80	.930

procedure in the selection process. No participant scored above 13 on the SDS so it was not necessary to exclude any participant due to the social desirability criteria. Fifteen participants who scored above 9 on the BDI (all fulfill HTA criteria) were excluded. Then, the final sample comprised 45 students (aged 18–25 years; 25 females and 20 males). None of them used medications affecting the cardiovascular or central/peripheral nervous system, or had any cardiovascular deficiency. Sighted participants used their eyeglasses or contact lenses. With respect to age and sex, significant group differences were not observed. Each student received course credit for their participation. Participants' consent was obtained according to the Declaration of Helsinki (World Medical Association, 2004).

2.1.1. Attention and decision-making tasks

Participants completed the following two tasks:

- The "Attention Network Test" (ANT, Fan et al., 2002), which measures the three attentional networks proposed by Posner and Dehaene (1994). We used a modified ANT task in which the stimuli are neutral faces that can look to the right or left. In each trial three faces appeared simultaneously on the screen after a fixation point, the participant had to press the "m" or "v" key as quickly as possible when the face in the centre of the screen looked to the right or left, respectively. In our study, the ANT was adapted to measure only the control-executive network. This specific attentional network has been associated at the neuropsychological level with frontal structures that are also linked to autonomic and cardiac regulation, including HRV (Duschek et al., 2013; Posner and Dehaene, 1994; Thayer et al., 2012). In the congruent trials, the two remaining distracting faces point in the same direction as the target face, while in the incongruent trials the distracting faces point in the opposite direction. In order to avoid non-valid responses, RTs shorter than 200 ms or longer than 1200 ms were excluded from the analysis (Callejas et al., 2005). The attentional control index was calculated as the difference in reaction times (RTs) between incongruent and congruent trials. Greater attentional control index values are then associated with poorer attentional control.
- The "Balloon Analog Risk Task" (BART; Lejuez et al., 2002). This task evaluates the assumed risk in decision-making, avoiding the drawbacks related to self-reporting measures. Participants were shown a balloon that could be inflated by pressing a button. Each pump involved a simulated gain of 25 cents. Participants could stop inflating the balloon at their discretion and save the amount of money obtained. The task included 30 balloons with varying probabilities of exploding. If the balloon exploded, the gains were lost. Therefore, participants were asked to decide the extent to which they could inflate each balloon: 25-cent potential gains vs. the risk of losing everything achieved so far with that balloon. A risk aversion index was calculated as the average number of inflation beats (excluding exploded ones). A lower number of inflation beats indicates greater risk aversion.

2.1.2. Self-reporting measures

The following three questionnaires were administered for sample selection:

- The Trait scale of the State-Trait Anxiety Inventory (STAI-T; Spielberger et al., 1970; Spanish version by Bermúdez (1978)). With scores ranging from 0 to 60, the internal consistency of the Spanish version ranges between 0.84 and 0.87 (Cronbach's $\alpha = 0.86$).
- The Beck Depression Inventory (BDI, Spanish version by Sanz and Vázquez (1998)). Its internal consistency (Cronbach's α) in non-psychiatric samples is 0.81 and the test–retest reliability (Pearson's r) ranges from 0.65 to 0.72.
- The Social Desirability Scale (SDS; Crowne and Marlowe, 1960; Spanish version by Ferrando and Chico (2000)). The internal consistency (Cronbach's α) ranges between 0.75 and 0.85, and its estimated time stability after 1 month (Pearson's r) is 0.89.

2.1.3. Heart rate variability

Electrocardiography (ECG) was recorded using disposable Ag/AgCI electrodes from Einthoven Lead II through a Biopac ECG amplifier (Biopac Systems Inc., Goleta, CA, USA) at 1000 Hz. Inter-beat interval (IBI) time series were extracted from ECG by R peak detection using the software Acknowledge (ver. 4.1; Biopac Systems Inc.). Before HRV analysis, IBI time series were visually checked for artifacts. When detected, they were corrected by linear interpolation. Missing R-waves were interpolated from surrounding beats and spuriously long beats were split into two similar equivalent IBIs, as recommended by Berntson et al. (1997). HRV was analyzed using the Kubios HRV program (ver. 2, Niskanen et al., 2004). An IBI time series was resampled at a frequency of 4 Hz to obtain equally spaced data points. Segments consisting of 256 data points with 50% overlap were cross-multiplied using a Hanning window and subsequently subjected to fast Fourier transformation (FFT) to derive HF-HRV within the 0.15 to 0.40 Hz frequency range (Berntson et al., 1997). Peak frequency of the HF-HRV component was taken as an index of respiratory rate (Thayer et al., 2002).

2.1.4. Procedure

The STAI-T, BDI and SDS questionnaires were completed in class groups. Once the final sample was selected and informed consent obtained, participants performed a single laboratory session. Following electrode placement, a baseline ECG was recorded during a 10-min period from which the last 5-min was taken for HRV analysis. Participants were asked to sit quietly and remain motionless during recording and were instructed to refrain from smoking, ingesting caffeine or alcohol, or performing vigorous exercise in the 2 h prior to the experiment. After the ECG recording, participants performed the ANT and BART tasks according to a between-subjects counterbalanced design, on a 17 inch screen with a resolution of 1024 × 768 pixels. The study protocol was approved by the Bioethics Committee of the University of Jaén.

2.1.5. Data analysis

Given that HRV measures in absolute units (ms^2) are usually positively skewed, HF-HRV was subjected to a natural log (ln) transformation to normalize its distribution. The statistical approach was selected in order to treat HF-HRV as a continuous variable. The main statistical analyses for both tasks were performed by General Lineal Models in which group (LTA vs. HTA), HF-HRV and the interaction group × HF-HRV were taken as predictor factors, and the attentional control index (for the ANT) and risk aversion (for the BART) as dependent variables (in a separate analysis). Analysis of possible group × HF-HRV interactions was performed by computing separate simple regression analyses (with HF-HRV as the predictor variable) in each anxiety group. The Bonferroni alpha correction was applied for multiple comparisons. Differences between mean scores were expressed as effect sizes with η_p^2 (partial variance explained for each independent variable). Variables were normally distributed (Shapiro–Wilk test $p > .05$), and Levene's tests confirmed homoscedasticity in all cases ($p > .05$). Associations between variables were computed by Pearson correlations. For illustrative purposes, and to facilitate the clarity of the results, a simple slope decomposition analysis was computed in which two groups were formed based on the HF-HRV median split (low vs. high HF-HRV subgroups). Statistical analyses were performed using the R statistical software package (R Foundation for Statistical Computing, Vienna, Austria). Once applied the Bonferroni correction, a .016 one-sided alpha level was used.

3. Results

Means and standard deviations of performance measures are displayed in Table 1. In the overall sample, without taking into account anxiety, HF-HRV was negatively associated with the attentional control index ($r = -.444$, $p = .002$) and positively associated with the risk aversion index ($r = .484$, $p = .001$). As HF-HRV becomes greater, attentional control improves and risk aversion decreases. The indexes of attentional control and risk aversion were negatively correlated ($r = -.775$, $p < .0001$), indicating that greater attentional control is associated with lower risk aversion. However, when this correlation was examined as a function of group it remained significant only in the HTA group ($r = -.764$, $p < .0001$) and not in the LTA group ($r = -.136$, $p = .55$). There was no group difference in HF-HRV or respiratory rate (see Table 1).

In the ANT task a significant main effect of group ($F(1,41) = 11.87$, $p = .001$, $\eta_p^2 = .22$, $1 - \beta = .92$) and a significant group × HF-HRV interaction ($F(1,41) = 7.76$, $p = .008$, $\eta_p^2 = .16$, $1 - \beta = .79$) were obtained ($R^2_{adj.} = .47$ for the whole model). The HTA group showed greater attentional control index values than the LTA group (see Table 1). Analysis of the interaction showed that HF-HRV predicted attentional control in the HTA group ($B = -4.22$, $SEB = 1.18$, $R^2_{adj.} = .340$, $t(22) = -3.6$, $p = .002$), but not in the LTA group ($B = 1.58$, $SEB = .96$, $R^2_{adj.} = .078$, $t(19) = 1.64$, $p = .117$). Fig. 1 displays the scatterplot of the relationship between HF-HRV and the attentional control index in the HTA group. Greater HF-HRV in the HTA group was associated with increased attentional control (i.e., lower interference). A simple slope decomposition of the interaction (Fig. 2), performed for illustrative purposes, revealed that in the HTA group greater HF-HRV was associated with increased attentional control. The only subgroup that clearly differed from the others and showed lower attentional control was the HTA group with low HF-HRV.

Concerning risk aversion in decision making, the analysis showed significant main effects of group ($F(1,41) = 11.15$, $p = .002$, $\eta_p^2 = .21$, $1 - \beta = .90$) and HF-HRV ($F(1,41) = 8.40$, $p = .006$, $\eta_p^2 = .17$, $1 - \beta = .81$), and a significant group × HF-HRV interaction ($F(1,41) = 4.18$, $p = .004$, $\eta_p^2 = .09$, $1 - \beta = .52$), with a value of $R^2_{adj.} = .69$ for the whole model. The LTA group showed greater risk aversion index values than the HTA group (see Table 1), while HF-HRV was positively associated with the risk aversion index ($B = 4.90$, $SEB = 1.34$, $R^2_{adj.} = .\ 217$, $t(44) = 3.63$, $p = .001$). Analysis of the interaction showed that HF-HRV was a significant predictor of risk aversion in the HTA group ($B = 5.26$, $SEB = 1.11$, $R^2_{adj.} = .479$, $t(22) = 4.70$, $p < .0001$) but not in the LTA group ($B = 0.91$, $SEB = 1.38$, $R^2_{adj.} = -.029$, $t(19) = .65$, $p = .52$). Fig. 1 displays the scatterplot for the relationship between HF-HRV and the risk aversion index in the HTA group. Greater HF-HRV in the HTA group was associated with an increased risk aversion index. As displayed in Fig. 2, a simple slope decomposition of the interaction revealed that in the HTA group greater HF-HRV was associated with an increased risk aversion index (lower risk aversion). The only subgroup that clearly deviated from the others and showed a lower risk aversion index was the HTA group with low HF-HRV.

4. Discussion

The results of the study show that individuals with high anxiety and low HF-HRV have worse attentional control in the face of conflicting information as well as greater risk aversion, in comparison to individuals with both high anxiety and high HF-HRV or low anxiety (regardless of the HF-HRV).

To date, studies have shown that HF-HRV moderates attentional and emotional processing with regard to threatening or emotional-salient stimuli (Gillie and Thayer, 2014; Greaves-Lord et al., 2010; Melzig et al., 2009; Miskovic and Schmidt, 2010; Park et al., 2013b; Ruiz-Padial et al., 2003; Ruiz-Padial and Thayer, 2014), and HF-HRV modulates the influence of trait anxiety on attentional processing with respect to emotion-driven stimuli (Bornas et al., 2005; Cocia et al.,

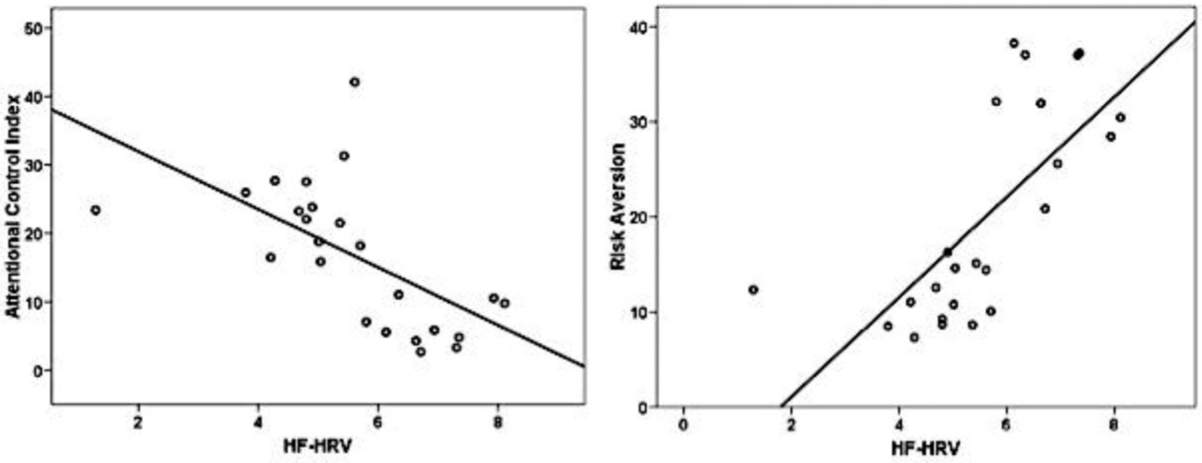

Fig. 1. Scatterplot and regression line for the relation between HF-HRV and attentional control index (left) and HF-HRV and risk aversion index (right) in the high trait anxiety group.

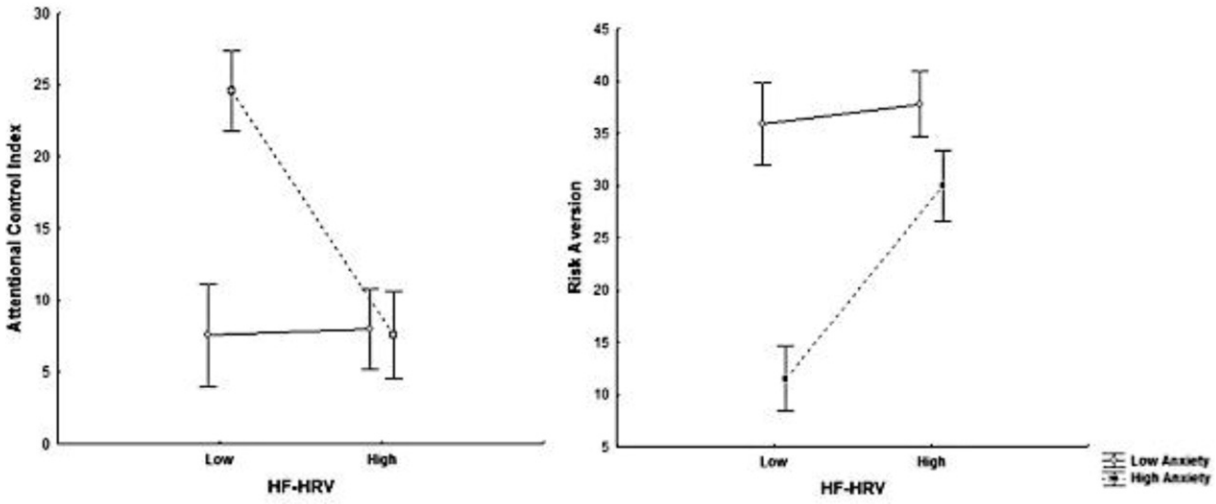

Fig. 2. Simple slope decomposition of the interaction between group (low vs. high anxiety) and HF-HRV (low vs. high HF-HRV) in predicting attentional control index (left) and risk aversion index (right).

2012). Building on these previous studies, our results extend this evidence by showing that HF-HRV also moderates the link between trait anxiety and cognitive biases towards neutral stimuli.

Regarding attentional control bias in anxious individuals towards neutral stimulation, our results are consistent with those of some other studies pointing out that anxiety is associated with deficits in executive control during the processing of neutral stimuli (Pacheco-Unguetti et al., 2011, 2012). Extending this previous evidence, our results showed that this bias is modulated by HF-HRV: in high anxiety participants HF-HRV explains 34% of the variance in attentional control; specifically, when anxious individuals exhibit high HF-HRV, their execution is similar to that of non-anxious individuals.

Individuals who have good attentional control are able to regulate their responses effectively and to focus on the demands imposed by a given task. HF-HRV is related to attentional control and individuals with high HF-HRV are better able to focus attention on the main task and are more efficient at ignoring distracting information, either emotional or neutral (Gillie and Thayer, 2014). According to the neurovisceral integration model (Friedman, 2007; Thayer et al., 2009; Thayer and Lane, 2000) low HF-HRV is indicative of decreased prefrontal inhibitory influences on sub-cortical structures, and by extension reduced attentional and emotional self-regulation (Park et al., 2013a; Thayer et al., 2009). This indicates a role for the autonomic nervous system in affective and cognitive functioning, which is supported by some previous studies (Bornas et al., 2005; Cocia et al., 2012; see Introduction section). It should be noted, as expounded in our third hypothesis, that when high trait anxiety was associated with greater HF-HRV, attentional control capacity did not differ from that of participants with low anxiety. The only condition that differs from the others, and in which attentional control is decreased, is when high anxiety is associated with low HF-HRV.

Incongruent trials confer a greater cognitive load than congruent ones given conflicting information presented. The participant must respond to the stimulus target and ignore conflicting information from other stimuli that accompany it in the incongruent condition. This conflict does not exist in the congruent condition in which, because there is no distracting information, the attentional demand of the task is lower (Lavie et al., 2004; Park et al., 2013a). When relevant and distracting stimuli are present, competition for attentional resources occurs. In order to implement effective top–down attentional control it is necessary to facilitate the perceptual processing of relevant stimuli in the task, and to inhibit irrelevant stimuli. Highly anxious individuals with high HF-HRV would have greater attentional control than those with high anxiety and low HF-HRV; these latter individuals would have difficulties in focusing attention on relevant stimuli and inhibiting the processing of irrelevant ones. This idea is supported by Park et al. (2013a), who found that low HF-HRV is associated with lower performance when neutral distractor stimuli are used, compared with high HF-HRV. Therefore our results suggest that cardiac vagal tone is associated not only with the inhibition of interference from outgoing emotional stimuli, but also with efficacy in controlling selective attention towards neutral distractors (Braver, 2012).

Anxious individuals displayed greater risk aversion than those with low anxiety. This result is in agreement with previous studies (Maner et al., 2007; Mitte, 2007; Miu et al., 2008; Ortega et al., 2012). If HRV is a predictor of cognitive control, it must also have a major influence on the decision making process. Accordingly, our results indicate that greater HF-HRV was associated with decreases in risk aversion, regardless of trait anxiety levels. This finding is in line with that obtained by Fooken and Schaffner (2013), who used a task involving choosing between games of chance. They found that individuals with low stress, indicated by high HRV, had lower risk aversion. However, Brunborg et al. (2010) found that HRV was related to executive functioning, but they did not observe any relationship between HRV and risk aversion during the Iowa Gambling Task. To the best of our knowledge, this is the first study explicitly addressing the interaction between trait anxiety and HF-HRV in determining risk aversion during decision making. Our results clearly show a modulatory influence of HF-HRV on the association between anxiety and risk aversion. In high trait anxiety participants, HF-HRV explained 48% of the variance in risk aversion. In this context, individuals with high HF-HRV displayed lower risk aversion than people with low HF-HRV. Similar to what was observed for attentional control, anxious participants with high HF-HRV did not differ from those with low anxiety in terms of risk aversion; only when high anxiety was associated with low HF-HRV did risk aversion increase.

It is worth highlighting the strong association between measures of attentional control and risk aversion. Individuals with greater executive-control attention capacity tend to take more risks in decision making, at least in a task like the BART. However, this general correlation should be viewed with caution as it is dependent on trait anxiety and remains significant only in the high anxiety group.

Increased risk aversion in individuals with low HF-HRV (especially in the context of high anxiety) is consistent with the reduced capacity for attentional control and emotional regulation found in individuals with low HF-HRV (Cocia et al., 2012; Thayer et al., 2009). These factors would increase the impact of anxiety on decision-making and could lead to a major conflict between risk taking and negative assessment of the possible consequences of decisions.

Assuming that HF-HRV indexes frontal influences on subcortical structures (Thayer and Lane, 2000), this result is coherent with neuropsychological theories of motivation and emotion (Davidson et al., 2000). The prefrontal cortex is considered to play a primordial role in the approach-related emotional-motivational system that mediates and facilitates appetitive behaviors (Davidson et al., 2000). Therefore, greater relative activity in some prefrontal cortex structures is expected to be associated with more risk taking in games with no real negative consequences, like the BART. Furthermore, the prefrontal cortex inhibits limbic regions such as the amygdala, which is a key structure in the withdrawal-related emotional system that facilitates withdrawal from sources of aversive stimulation (Davidson et al., 2000). The amygdala plays a pivotal role in directing attention to affectively-negative salient stimuli, negative affect generation, and emotional-related physiological reactivity. From the point of view of the somatic marker hypothesis of decision making (Bechara et al., 2005), increased prefrontal activity will lead to diminished amygdala activity and lower emotional reactivity (i.e., lower somatic marker inhibitory influences on decision making). Therefore, it can be predicted that greater HF-HRV would be associated with more risk taking in tasks like the BART, in which no real negative consequences exist. Thus, autonomic activity and reactivity may be important factors in the decision making process, although it cannot be established whether autonomic arousal affects decision-making directly or is just an index of neural processes at the cortical level (Drucaroff et al., 2011).

This line of research may have practical applications, for example with respect to the study of the effects of interventions aimed at increasing HRV (e.g., physical exercise, diet, biofeedback, drugs, etc.) on attentional control, decision making under risky conditions, and preventing or reducing anxiety disorder relapses. This could benefit people with low HF-HRV and stress-related hyper-vigilance. These conditions can trigger a cascade of physiological and psychological responses at a defensive level that, in turn, would affect other physiological systems and cause long-term health problems such as hypertension, coronary heart disease, diabetes, etc. (Park et al., 2014).

High anxiety has been associated with lower HF-HRV (e.g., Watkins et al., 1998), and low HF-HRV has been found in several anxiety disorders (Gillie and Thayer, 2014; Pittig et al., 2013). In our study, no difference in HF-HRV was observed between the high and low trait anxiety groups. As an explanation for this negative result, our sample was composed of young participants with subclinical anxiety levels, but without clinical anxiety disorders. Other studies in this field with similar samples have also obtained no differences in HF-HRV as a function of trait anxiety levels (e.g., Cocia et al., 2012).

Regarding the limitations of the study, the sample size is small for a moderating study, which may have compromised the statistical power and increased the probability of both type I and type II errors. If the statistical power curve is calculated considering a power value of .80 and a conventional significant level of .05, the sample size needs to obtain a moderate effect size of .30 with 49 participants per group (i.e., it would be necessary to duplicate the sample size currently used). In view of this limitation, the results found should be treated with caution and considered preliminary; there is a need for replication using larger samples. Second, the sample is composed of young participants (<26 years) and the results cannot be directly extrapolated to older samples. This may be particularly relevant because cardiac vagal activity tends to decline with age (Berntson et al., 1997). We measured HF-HRV during a previous resting period and not during the actual performance of the tasks. Associations between attentional performance and physiological parameters (including HRV) could vary depending on whether the physiological variables are measured at rest or during task performance (Duschek et al., 2009; Kimhy et al., 2013). Future studies should assess the relationship between attentional control, risk aversion, and HF-HRV measured during actual performance of the tasks. Finally, future studies should replicate the results obtained with the BART using more complex decision-making tasks, such as those involving choices with associated losses or gains, dilemmas or the Iowa Gambling Task.

Concerning the methodological strengths of the study, two points can be made. HF-HRV is affected by changes in respiration (Berntson et al., 1997). We measured respiratory rate by peak frequency HF-HRV (Thayer et al., 2002) and found no group differences, thereby discounting the possibility that the results could be a consequence of secondary respiratory influences. Anxiety and depression are highly interlinked; a strong association with depression could confound the relationship between anxiety and other variables. In our study, we controlled for depression levels and excluded participants with depression symptoms.

In conclusion, although the results of the study should be taken as preliminary and needs replication, they suggest that HF-HRV modulates the influence of anxiety on both attentional control and risk aversion in decision making. In highly anxious individuals, greater HF-HRV exerts a protective effect, leading to similar attentional control and risk aversion as seen in low anxiety individuals. It was only in high anxiety persons with low HF-HRV that both attentional control biases and greater risk aversion were observed. Finally, the strong relationship found between attentional control and risk aversion suggests that executive control of attention can play a relevant role in risk taking, suggesting a need to analyze the relationship between inter-individual differences in attentional executive-control and risk aversion.

Conflict of interest

No conflict of interest has been declared by the authors.

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