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Studying the dynamics of autonomic activity during emotional experience

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Abstract

Recent theories emphasize the dynamic aspects of emotions. However, the physiological measures and the methodological approaches that can capture the dynamics of emotions are underdeveloped. In the current study, we investigated whether moment-to-moment changes in autonomic nervous system (ANS) activity are reliably associated with the unfolding of emotional experience. We obtained cardiovascular and electrodermal signals from participants while they viewed emotional movies. We found that the ANS signals were temporally aligned across individuals, indicating a reliable stimulus-driven response. The degree of response reliability was associated with the emotional time line of the movie. Finally, individual differences in ANS response reliability were strongly correlated with the subjective emotional responses. The current research offers a methodological approach for studying physiological responses during dynamic emotional situations.

Descriptors: Electrodermal, Heart rate, Emotion, Intersubject correlation, Continuous physiological signals, Dynamic emotional experiences

Autonomic nervous system (ANS) activity is viewed as a major component of the emotion response (Bradley & Lang, 2000; Codispoti, Bradley, & Lang, 2001; Critchley & Nagai, 2012; Damasio, Tranel, & Damasio, 1991; James, 1884; Kreibig, 2010; Levenson, 2003; Mauss & Robinson, 2009; Stemmler, 2004). Accordingly, the ANS responses associated with various emotional states have been extensively investigated in psychophysiology research. The leading methodology in this research employs average reactivity indexes either by presenting very short stimuli and averaging ANS responses across presentations (e.g., assessing the average amplitude of instantaneous responses elicited by emotional pictures) or by aggregating ANS activity across time (e.g., assessing the differences of average ANS activity in emotional vs. neutral movies).

The usage of average reactivity indexes requires discrete events, focusing on the peaks of emotional experience rather than on its unfolding (Frijda, 1988). However, emotional experiences arise from continuous interaction with complex, fast-changing internal and external environments. Indeed, recent theoretical frameworks are emphasizing the dynamic aspects of emotional processes, conceptualizing emotions as emerging interactive processes (Barrett, 2006; Barrett, Mesquita, Ochsner, & Gross, 2007; Frijda, 1988; Scherer, 2009). The investigation of emotional experiences as dynamic, contextual processes requires an alternative methodological approach that can reflect the dynamics of unfolding emotional events. One such approach is to examine the ongoing changes in autonomic activity, such as the moment-to-moment fluctuations of electrodermal or cardiovascular measures, which can capture the temporal aspects of physiological responses. However, the reliability of continuous ANS signals and their relation to the unfolding emotional experience have been largely underinvestigated in the psychophysiology research (Kettunen & Ravaja, 2000; Kettunen, Ravaja, Näätänen, Keskivaara, & Keltikangas-Järvinen, 1998).

Initial evidence for the usefulness of continuous ANS responses comes from a series of recent studies that investigated the within-individual response coherence of ANS signals (Hsieh et al., 2010; Kettunen & Keltikangas-Järvinen, 2001; Kettunen et al., 1998; Mauss, Levenson, McCarter, Wilhelm, & Gross, 2005). These studies demonstrated that fluctuations of various ANS measures are synchronized (i.e., coherent) within an individual. In addition, these studies showed that the degree of such response coherence can be affected by meaningful psychological factors (Hsieh et al., 2010; Kettunen et al., 1998; Mauss et al., 2005). For example, Mauss et al. (2005) studied continuous response patterns to emotional movies and showed that within-individual coherence between cardiovascular and electrodermal measures was affected by the intensity of subjective emotional experience. In the context of the current work, these studies provide evidence that continuous fluctuations of ANS activity carry reliable information, which is coherent within an individual, and can be used to study subjective emotional experiences over time.

The above-mentioned studies employed within-individual analysis, investigating synchronization of various ANS measures within individuals. However, investigation of specific stimulus-

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response effects requires across-individual designs. Specifically, in the case of dynamic processes, it is still unclear whether continuous ANS signals exhibit time-locked response patterns that are consistent across individuals. At least two sources of variability can impede the existence of such across-individual reliability (i.e., reproducibility) of continuous signals. First, the ANS responses contain individual-specific components, accounting for a significant portion of variance in psychophysiological measures (Marwitz & Stemmler, 1998; Stemmler & Wacker, 2010). For example, both EDA lability and HR reactivity were shown to be consistent individual characteristics (Manuck, Kasprowicz, Monroe, Larkin, & Kaplan, 1989; Schell, Dawson, & Filion, 1988). Such an individual-specific autonomic component increases the intersubject variability and diminishes the across-individual response consistency. A second source of variability that can hamper the stimulus-response linkage of continuous signals is that the ANS activity is prone to multiple physiological and environmental factors that may arise in parallel to emotion-related activations. These background factors, such as ambient temperature, circadian rhythm, general arousal, body posture, mental effort, anticipation, and cognitive load (Berntson & Cacioppo, 2000; Stemmler, 2004) give rise to additional, stimulus-unspecific components of variance in the ongoing ANS signals. Hence, whether time-locked stimulus-response linkage will be evident in moment-to-moment changes of the ANS activity above and beyond individual response characteristics, background processes, and measurement noise remains an open question.

In the current research, we investigated the across-individual reliability of continuous ANS signals, elicited by emotional movies. In addition, we asked whether such reliability is associated with the emotional experience induced by the movies. To that aim, we applied an intersubject correlation (interSC) analysis (Golland et al., 2006; Hasson, Nir, Levy, Fuhrmann, & Malach, 2004; Hasson, Yang, Vallines, Heeger, & Rubin, 2008) that quantifies the extent to which continuous response time courses covary across individuals. If emotional movies induce reliable (i.e., consistent across participants) ANS changes, we would expect to find a high degree of similarity across the individual ANS response time courses. We applied the interSC analysis to both the cardiovascular (heart rate; HR) and the electrodermal (EDA) measures and assessed whether stimulus-locked temporal response patterns can be found across individuals. In addition, we investigated the relation between across-individual reliability (i.e., interSC) and within-individual response coherence (i.e., intraSC, the correlation of HR and EDA signals within individuals). Previous studies suggested that, in emotional contexts, the within-individual response coherence is affected by the intensity of subjective emotional experience (Mauss et al., 2005). To the extent that movies induce consistent emotional experience across subjects, we hypothesized that the dynamics of the interSC and intraSC would be highly related. Finally, we studied whether across-individual reliability measures were associated with the emotional time line of a prolonged movie excerpt (Study 1) and with the subjective emotional responses to short movie segments that contained specific emotional context (Study 2).

Study 1

The aim of this study was to investigate the across-individual reliability of continuous HR and EDA signals, elicited by emotional films. Films are frequently used in the research on psychophysiology of emotional responses as they naturally and automatically elicit emotional states (e.g., Gross & Levenson, 1995; Kreibig, Wilhelm, Roth, & Gross, 2007). In contrast to previous studies, which mainly used short segments of movies in order to induce specific emotions, we used a prolonged cinematic excerpt (36 min) containing a mixture of emotional states. This enabled us to investigate the unfolding of a complex emotional experience in time. In this study, we assessed (a) whether the HR and EDA measures exhibit time-locked temporal responses that are correlated across individuals; (b) whether across- and within-individual coherence measures have similar dynamics, that is, are similarly modulated by the movie time line; and (c) whether these modulations are driven by the emotional aspects of the movie.

Method

Participants. Twenty-seven students participated in the study for course credits (mean age = 20 ± 1.7 *SD*, 18 females). Written informed consent was obtained after the procedure had been fully explained.

Materials and procedure. Participants were tested individually in a quiet and comfortably lit room. The stimulus in Study1 was the first 36 min of the cinematic film “Mystic River” (Eastwood, 2003). Participants were hooked to physiological sensors and watched the movie after an accommodation period. After the movie ended, they were given a free recall test, in which they were requested to recall and describe up to five of the most arousing scenes from the movie.

Physiological measures: Collection and preprocessing. During the experimental session, continuous physiological measures were recorded at a sample rate of 1 kHz with an integrated system and software package (Mindware, Gahanna, OH). Three measures were obtained, that is, electrocardiogram (ECG), EDA, and respiration (not analyzed in the current study). Cardiovascular responses were recorded with the ECG amplifier module and disposable snap ECG electrodes using a modified lead II configuration. The heart period (interbeat interval or IBI) was assessed using the Mindware HRV 2.16 Biosignal Processing module that included (a) identifying the R–R intervals, (b) detecting physiologically improbable R–R intervals based on the overall R–R distribution using a validated algorithm (Berntson, Quigley, Jang, & Boysen, 1990), and (c) manual inspection to ensure that R-waves were correctly identified. These IBI series were then transformed to continuous 2 Hz HR time series using inhouse software. Skin conductance level was recorded using Beckman electrodes attached to the palmar surface of the middle phalanges of the first and second fingers of the nondominant hand. Continuous (2 Hz) EDA signals were extracted using Mindware's EDA 2.1 software.

The resulting two Hz EDA and HR time series were manually examined for gross motion artifacts and for detection of nonresponsive participants. This led to the exclusion of four participants that showed nonresponsive EDA signals. Two more participants were excluded due to gross artifacts, leaving 21 subjects for the subsequent analysis. For the remaining participants, the first 60 s were removed from the data to reduce nonspecific adaptation effects. EDA signals were smoothed, using a 10-s long moving average (Kettunen, Ravaja, & Keltikangas-Järvinen, 2000), and linear trends were removed. HR signals were low-pass filtered (below 0.04 Hz) to remove the fast, idiosyncratic component of HR variability. Finally, all signals were z normalized.

Continuous ratings of emotional arousal. Using an independent sample of participants ($N = 13$, mean age $= 21 \pm 1.1$, 10 females), we collected continuous ratings of the intensity of emotional experience induced by the movie. The ratings were done using a 270º rating dial (values: 0–40), which is an integral part of the MindWare recording system. Participants provided continuous ratings of their emotional arousal, while they watched the experimental movie. Individual time series of subjective responses were resampled to 10 Hz, and averaged across the participants.

Data analysis

Intersubject correlation analysis. To assess response reliability of continuous HR and EDA signals, we applied interSC. The interSC provides a measure of the across-subject reliability of physiological responses by quantifying the commonalities of the response time courses among individuals exposed to the same stimulus. To assess the commonalities between two given physiological time courses, we applied cross-correlation analysis, which indicates the extent to which these response time courses covary, while taking into account lags between the responses. We constrained the temporal shift between the two time courses to ± 10 s (e.g., Kettunen et al., 2000; Mauss et al., 2005). For each individual, we first calculated an individual interSC, defined as $r_j = r(x_j, \bar{x})$, where r_j is the maximal correlation within ± 10-s lags, between x_j, the response time course of individual j, and $\bar{x} = \sum_{i \neq j} x_i$, the average response time course of all other individuals (i.e., not including individual j). Groupwise interSC was computed as $R = \frac{1}{N}\sum_{j=1}^{N} r_j$. This analysis was done for each response system separately, yielding two measures of reliability: interSC_{EDA} and interSC_{HR}.

Bootstrapping procedure using surrogate data. To account for different confounding factors in the physiological signals (such as autocorrelations), which might lead to spurious null correlations, the statistical likelihood of the observed groupwise interSC was assessed nonparametrically, using surrogate data that preserves the temporal and the spectral characteristics of the experimental time series. The surrogate data was produced by applying discrete Fourier transform to the signal, then randomizing the phase of each Fourier component and inverting the Fourier transformation. This procedure scrambles the phase of the physiological time course but leaves its power spectrum intact.

We tested the groupwise interSC (R), against the null hypothesis that subjects' time courses are not correlated. The control sampling distributions (presented in the online supporting information Figure S1a) were estimated empirically for each autonomic measure by (a) creating $N = 21$ surrogate time courses, (b) calculating groupwise interSC for those time courses, and (c) repeating this procedure 1,000 times. Under the null distribution, the mean and the standard deviations of the groupwise interSC_{EDA} was 0.083 ± 0.08 and of the groupwise interSC_{HR} was 0.038 ± 0.03; the p values for the experimental groupwise interSCs were directly estimated from the cumulative null distribution.

Intrasubject correlation (intraSC) analysis. We assessed within-individual response coherence (intraSC) by computing the maximal cross-correlation within ± 10-s lags between individual EDA and HR time courses (see Kettunen et al., 2000; Mauss et al., 2005, for a similar approach).

Temporal windows analysis. To assess how the interSCs and the intraSC change along the movie time line, we performed a moving windows analysis, using short ($t = 60$ s), overlapping ($\Delta t = 30$ s) time segments. For each time window, we computed the maximal correlation (within ± 10-s lags) between the time course of each individual with all the other time courses in the group, yielding an $\text{interSC}_{HR(W)}$ time course and $\text{interSC}_{EDA(W)}$ time course for each individual in the group. The individual $\text{intraSC}_{EDA\_HR(W)}$ time courses were computed in the same time windows, using the maximal cross-correlation (within ± 10-s lags) between the same individual's HR and EDA time courses. The statistical likelihood of those measures in each time window was assessed nonparametrically (against synthetic control data), yielding a series of p values. These p values were corrected for multiple comparisons, using the false discovery rate (FDR) procedure for positively dependent tests (Benjamini & Yekutieli, 2001).

To compare the dynamics of the $\text{interSC}_{EDA(W)}$, $\text{interSC}_{HR(W)}$, and $\text{intraSC}_{EDA\_HR(W)}$, we calculated Pearson correlations between these time courses for each individual, using nonoverlapping 60-s windows (to reduce the dependency between two consecutive windows). The significance of each comparison was tested using t tests on Fisher z-transformed correlation coefficients (Table 1, individual measures). Similar analysis was conducted for the average time courses of these three measures, aggregated across individuals. The statistical significance of each comparison for the average time courses was assessed nonparametrically, using bootstrapping procedure (Table 1, group measures).

Supporting information Figure S2 presents a working example of the interSC approach, from individual response time courses to individual and group measures of the interSC and $\text{interSC}_{(W)}$.

Results

Across-individuals reliability of cardiovascular and electrodermal responses. Both HR and EDA responses were significantly correlated across individuals during the free viewing of an emotional movie (groupwise $\text{interSC}_{EDA} = 0.41$, $SD = 0.22$, $p < .001$; groupwise $\text{interSC}_{HR} = 0.34$, $SD = 0.14$, $p < .001$). Moreover, we found that the degree of individual interSC_{EDA} was significantly correlated with the degree of individual interSC_{HR} ($r = .43$, $p < .03$, see supporting information Figure S1b). Thus, subjects who were more synchronized with others in EDA (higher interSC_{EDA}) were also more synchronized with others in HR (higher interSC_{HR}).

The fact that we obtained high and significant interSC in both ANS measures indicates that individual ANS responses contain a robust stimulus-driven component, which is shared across individuals. To model the shared component, we computed average ANS response time courses, thus diminishing the interindividual variability and enhancing the shared component. The upper panel of Figure 1a presents the average response time course of normalized EDA (blue) and HR (red) activities. As can be seen in the figure, there is a high correspondence between average EDA and HR response time courses, both in the fast, phasic components and in slow, tonic trends, with the cardiovascular changes preceding the slower, electrodermal changes (max $r = .47$, lag = 25 s).

To further assess the consistency of the average response time courses, we divided our sample into two subsamples in a semi-random procedure ($n1 = 10$, $n2 = 11$). The lower panel of Figure 1 presents the average time courses from these two subsamples, which exhibited robust correlations both within-measure, across subsamples, r(EDA1-EDA2) = .68; r(HR1-HR2) = .64, and

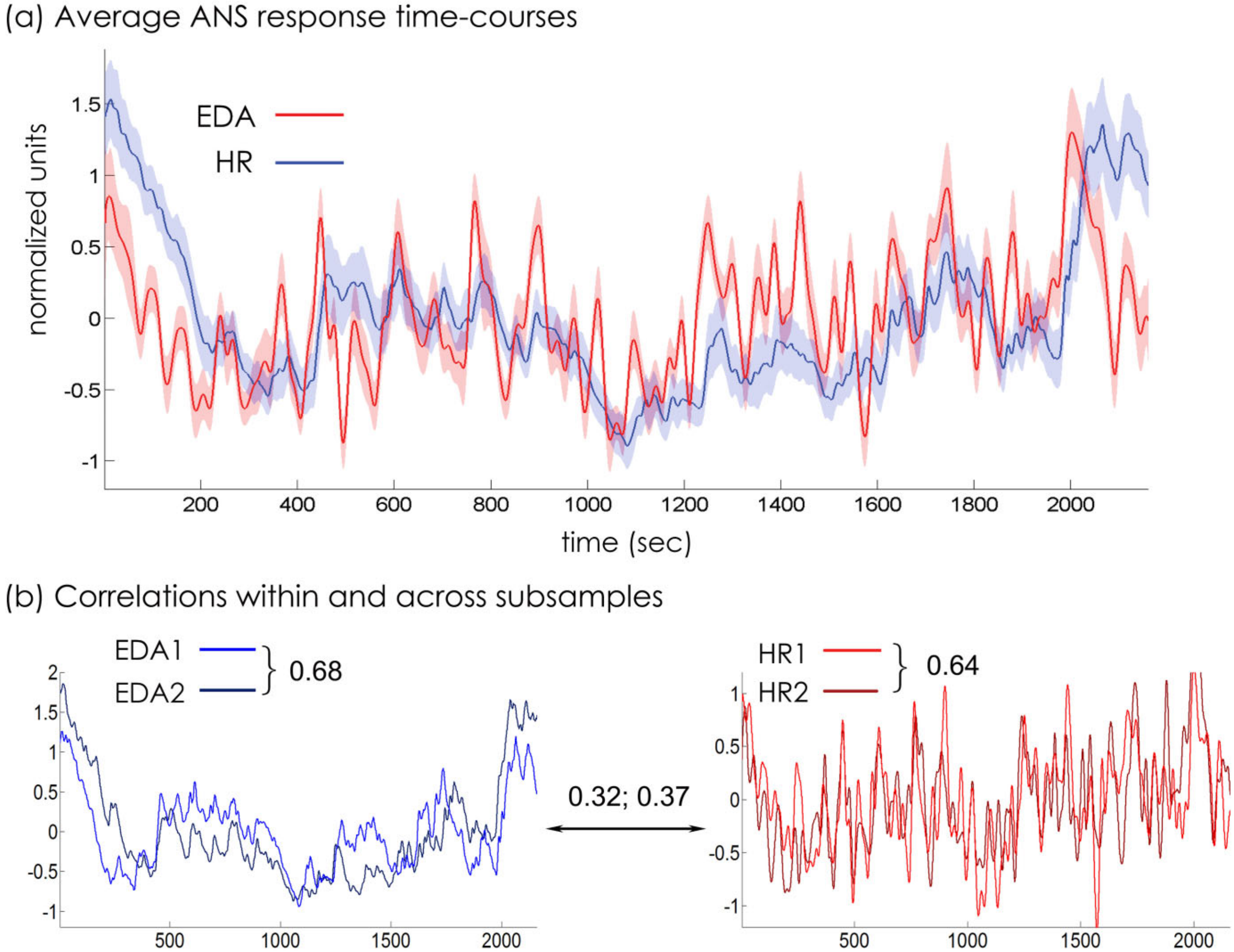

Figure 1. Average autonomic response time courses. a: Continuous EDA (blue) and HR (red) response time courses, averaged across subjects. Shaded areas represents standard deviations of the average measures. b: Continuous EDA (dark/light blue) and HR (dark/light red) response time courses, averaged across two subsamples ($n1 = 11$, $n2 = 10$). To assess the reliability of average response time courses, we computed within-measure, across subsamples correlations: r(EDA1-EDA2) = 0.68; *r*(HR1-HR2) = 0.64; and across-measures, across subsamples correlations: *r*(EDA1-HR2) = 0.32, *r*(EDA2-HR1) = 0.37.

across-measures, across subsamples, *r*(EDA1-HR2) = 0.32, lag = 27 s; *r*(EDA2-HR1) = .37, lag = 28 s). Nonparametric statistical procedure showed that all of these correlations were significant ($p < .001$). These robust correlations across subsamples and across response systems suggest that average ANS response time courses display meaningful and coherent temporal patterns, which are consistent across subjects and across measures.

Dynamics of interSC and intraSC measures across the movie time line. Next, we investigated whether the coherence of ANS responses, both across and within participants, changes along the movie time line. To that aim, we computed the interSC$_{HR}$, interSC$_{EDA,}$ and the intraSC$_{EDA_HR}$ measures in short temporal windows (hereafter, interSC$_{HR(W)}$, interSC$_{EDA(W)}$, and intraSC$_{EDA_HR(W)}$—see Methods).

Figure 2a displays how the interSC$_{HR(W)}$, interSC$_{EDA(W)}$, and intraSC$_{EDA_HR(W)}$ changed at different times of the movie. As evident in Figure 2a, the dynamics of those three indexes were highly similar. In other words, specific time windows during the movie were characterized by enhanced coherence of the ANS responses. This alignment of responses in specific time windows occurred for each ANS measures across individuals (interSC$_{HR(W)}$, interSC$_{EDA(W)}$) and across measures, within individuals (intraSC$_{EDA_HR(W)}$). Table 1 presents the correlations between the two interSC$_{(W)}$ and the intraSC$_{(W)}$ measures, computed for individual and for average time courses (see Methods).

Table 1. *Correlations Between interSC$_{EDA(W)}$, interSC$_{HR(W)}$, and intraSC$_{EDA_HR(W)}$, Computed for Individual Measures and for Group Measures*

	Group	Individual
interSC$_{EDA(W)}$–interSC$_{HR(W)}$	0.51*	0.17 ± 0.18*
interSC$_{EDA(W)}$–intraSC$_{EDA_HR(W)}$	0.64*	0.27 ± 0.11*
interSC$_{HR(W)}$–intraSC$_{EDA_HR(W)}$	0.53*	0.17 ± 0.17*

*$p < .01$.

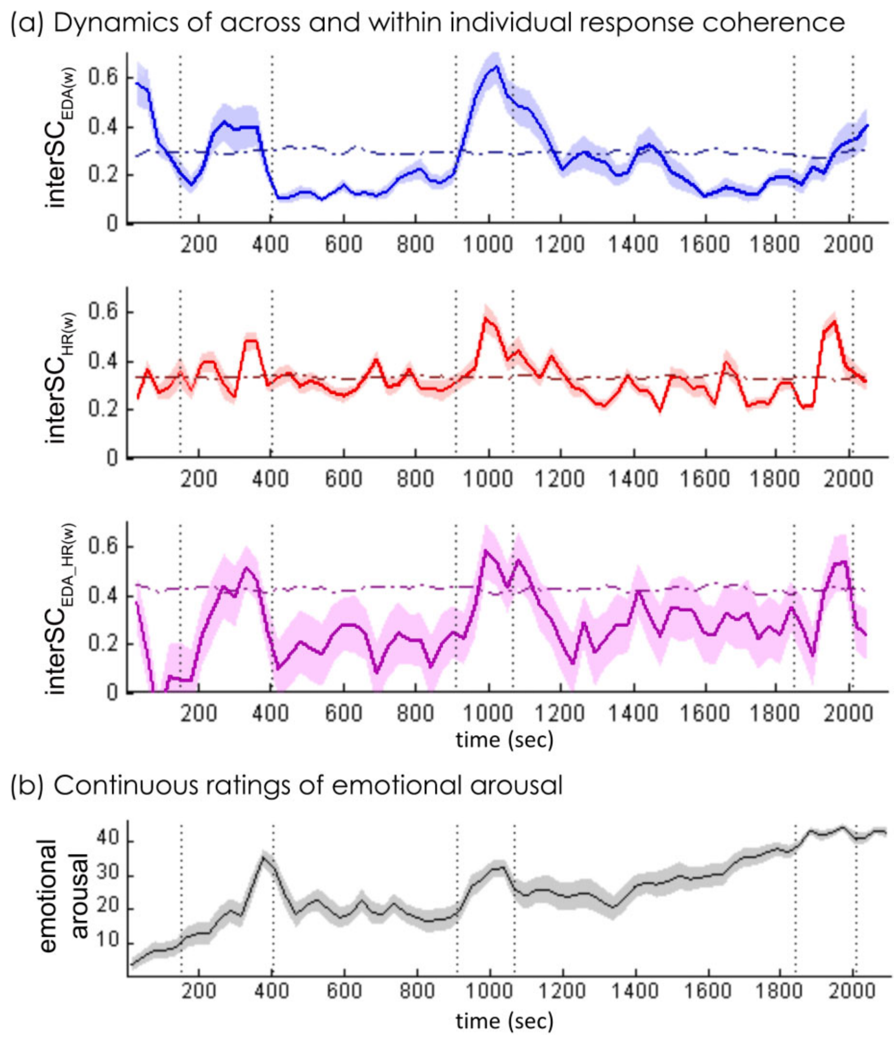

Figure 2. Dynamic modulations of interSC and intraSC along the movie time line. a: Dynamics of across- and within-individual response coherence. The figure presents $interSC_{EDA(W)}$, $interSC_{HR(W)}$, and $intraSC_{EDA\_HR(W)}$ computed in temporal windows (60 s), and averaged across subjects. Horizontal lines mark significance index (corrected for multiple comparisons, FDR: $q < .05$). Vertical lines mark the three most emotional scenes, recalled by the majority of the subjects after the experiment (proportion > 0.86). b: Continuous ratings of emotional arousal. Average continuous ratings of emotional arousal, obtained from independent subject pool.

Exploratory analysis: Dynamics of interSCs and intraSC are associated with the emotional intensity of the movie. As is evident in Figure 2a, both inter- and intrasubject windowed correlations rise simultaneously above the significance level at three time periods during the movie. Notably, the three time periods coincide with the most emotionally intense movie scenes, as reported by the participants after viewing the movie (marked by vertical lines in Figure 2a). To qualitatively validate this observation, we used the continuous rating of emotional arousal obtained from the independent sample (see Methods). As can be seen in Figure 2b, the peaks of emotional arousal fall in the three time periods, which match the times of the interSCs and intraSC increases.

Discussion

In Study 1, we investigated the reliability of cardiovascular and electrodermal response time courses elicited by a prolonged movie excerpt with mixed emotional states. We found that, despite its complexity, the movie elicited reliable ANS activity, which was temporally aligned across individuals. Averaging ANS response time courses across individuals allowed for the estimation of the movie-driven common component. Both EDA and HR average signals exhibited strong within-measure reproducibility, indicating highly reliable stimulus-driven effects. Notably, the across-measures correlations between average EDA and average HR were lower (although still reliable), suggesting that average signals preserve the physiological response characteristics of the particular ANS subsystem.

Time-sensitive analysis showed that the ANS response reliability wasn't constant, but exhibited significant changes along the movie time line. The response reliability of both HR and EDA measures raised above the significance level during the most emotionally arousing episodes of the movie (Figure 2). Notably, the within-individual HR-EDA response coherence was elevated during the same periods. The within-individual ANS response coherence (i.e., intraSC) is modulated by the intensity of subjective emotional experience (Mauss et al., 2005). The across-individual response coherence (i.e., interSC) indexes stimulus-response effects. Our results suggest that the movie induced consistent emotional experience across individuals, resulting in similar responses both across individuals and within individual, across measures.

Study 2

The main aim of this study was to provide further evidence for the relation of interSC to the intensity of emotional experience. For that aim, we measured EDA and HR signals while participants viewed short film excerpts with specific emotional content (amusing and fearful) or with neutral content. We calculated interSC for each type of movie and for each autonomic measure (i.e., HR and EDA) and assessed its relationship to participants' subjective emotional responses.

Method

Participants. Twenty-two female students participated in the study for course credits (age: 21 ± 2.3). Written informed consent was obtained after the procedures had been fully explained.

Materials and procedure. Stimuli in this study consisted of two short emotional movies and two short neutral movies. The positive emotional movie (hereafter, positive movie) consisted of three excerpts from the comedy "When Harry Met Sally" (Reiner & Scheinman, 1989; 447 s). The middle excerpt was a well validated amusing scene (Gross & Levenson, 1995; 203 s). In order to enrich emotional variability, necessary for the interSC analysis, we inserted the validated scene between a short introductory scene from the beginning of the movie (106 s) and an emotional scene from the end of the movie (138 s). The negative emotional movie (hereafter, negative movie) consisted of three excerpts from the horror film "Paranormal Activity" (Blum & Peli, 2007; 419 s). The first scene (80 s) presented interaction between the movie figures, which provides contextual information for the following scenes, the second scene (113 s) involved a prolonged frightening event, and the third scene (226 s) involved anxious anticipation that ended with a rapid frightening event. This movie was chosen after an exploratory pilot stage, which showed that it induces high levels of fear. Each emotional movie was preceded by a brief summary of the movie's plot, presented on the screen for 60 s. The two emotionally neutral movies (hereafter, neutral1 and neutral2), consisted of nature scenes with background music (180 s).

Participants were hooked to physiological sensors and, after an accommodation period lasting about 4 min, watched the movies (neutral1, positive; neutral2, negative) in a counterbalanced order.

Measures of emotional experience. Following each emotional movie, participants rated the degree of seven distinct emotions elicited by the movie (joy, anxiety, confusion, embracement, fear, amusement, and surprise), using an 11-point Likert-like scale (Gross & Levenson, 1995). In addition, participants provided ratings of valence and arousal for both emotional and neutral movies.

Physiological measures: Collection and preprocessing. Physiological recordings and preprocessing details are identical to Study 1. Individual EDA and HR time series were examined for motion artifacts and unresponsive subjects. The final data set contained 20 HR time series and 13 EDA time series for positive movie and neutral1 experimental conditions, and 20 HR time series and 15 EDA time series for negative movie and neutral2 experimental conditions.

Data analysis. We computed interSC$_{EDA}$, interSC$_{HR,}$ and intraSC$_{EDA_HR}$ for both emotional movies and for both neutral movies, and assessed its statistical likelihood using the same approach as described in Study 1. In addition, we calculated reactivity scores for each autonomic measure (EDA, HR) and for each emotional movie (positive movie, negative movie), by averaging the sample points across the movies' durations, and subtracting average scores of each neutral movie from average scores of the immediately following emotional movie.

Results

Descriptive physiological and emotional characteristics of the movies. We calculated a series of emotional and physiological measures for each neutral movie and for each emotional movie (Table 2). To assess the emotional effects of the movies, we calculated the mean rates of arousal and valence. Both emotional movies were more arousing than the neutral movies (positive movie: $t(22) = 7.15$, $p < .00$; negative movie: $t(22) = 9.1$, $p < .00$). In addition, positive movie was rated as more positive, $t(22) = 5.4$, $p < .0$, and negative movie was rated as more negative, $t(22) = 4.8$, $p < .0$, than the neutral movies.

To assess average ANS response profiles elicited by the movies, we calculated the mean scores of EDA and HR data samples, across the movies' duration. These physiological variables were tested for univariate significant differences between emotion conditions (fear, neutral, and amusement) by repeated measures analysis of variance (ANOVA). This analysis revealed a significant effect of movie type for negative movie ($p < .03$) and a nonsignificant effect for positive movie ($p < .3$). We speculated that the average effect of the positive movie on ANS responses degenerated due to the combination of additional scenes in the assessment period. Hence, we used the average temporal profile of HR and EDA responses to better capture the time periods of the induced emotional arousal. Figure 3 presents the average temporal responses of both ANS measures during neutral and emotional films. As can be seen in the figure, both EDA and HR display dynamic responses, with multiple changes across the experimental time line. Using these response profiles, we optimized the definition of the time windows for which average scores were calculated (marked by gray rectangles in Figure 3).

Specifically, neutral movie measures were limited to the last 60 s. For positive movie, the emotional period was limited to the distinctive middle peak of arousal, associated with the main amusement scene in the movie (201-s duration). For negative movie, the first neutral scene was excluded from the analysis (718-s duration).

Table 2. *Emotional Responses, Mean ANS Scores, and interSC Measures During Emotional and Neutral Movies*

	Neutral1	Positive movie	Neutral2	Negative movie
Arousal	1.96 ± 1.94	5.70 ± 1.46	1.96 ± 1.94	6.35 ± 1.30
Valence	4.87 ± 1.52	6.78 ± 0.90	4.87 ± 1.52	2.04 ± 1.85
HR	79.5 ± 9.6	75.99 ± 9	79.3 ± 8.01	77.25 ± 9.73
EDA	2.77 ± 3.03	3.49 ± 2.97	3.1 ± 2.62	3.8 ± 2.54
interSC$_{HR}$	0.12 ± 0.29	0.24 ± 0.20	−0.07 ± 0.19	0.32 ± 0.11
interSC$_{EDA}$	0.09 ± 0.44	0.58 ± 0.23	0.08 ± 0.41	0.52 ± 0.2

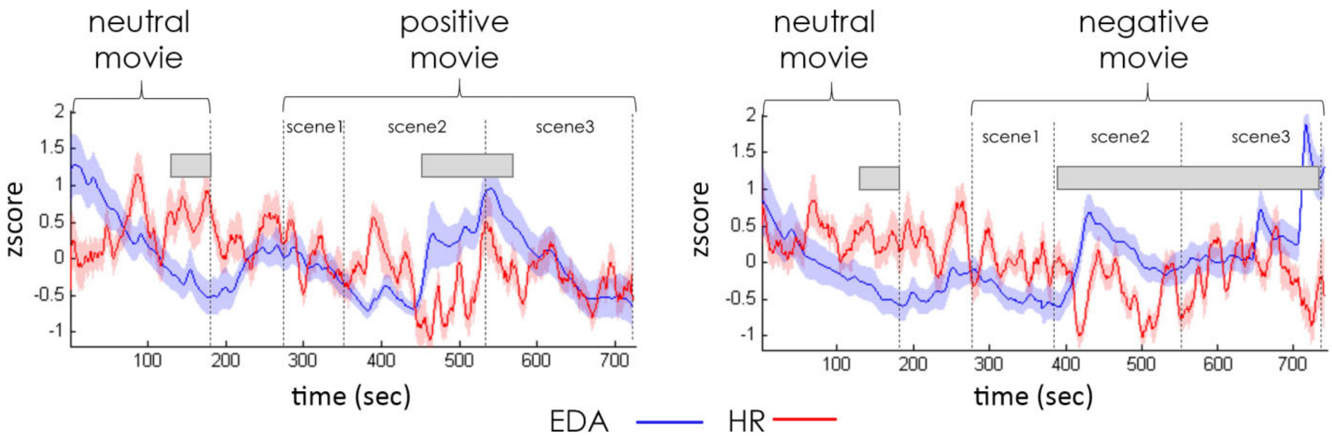

Figure 3. Average ANS response time courses during neutral and emotional scenes. The figure presents HR and EDA normalized response time courses, averaged across participants. Both positive movie (left panel) and negative movie (right panel) were preceded with neutral movie and short text presentation of the movie plot. The emotional movie excerpts included three different scenes (marked by dotted lines). Gray rectangles represent optimized experimental periods for the calculation of mean scores and reactivity scores.

The recalculated mean scores (Table 2) showed stronger emotion-related effects, exhibiting significant effects of the movie type for both emotional movies. Planned comparisons for positive movie versus neutral movie showed significant difference in mean HR, $t(19) = -5.465$, $p < .00$, and marginally significant effect in mean EDA, $t(12) = 1.69$, $p < .11$. For negative movie, both mean HR and mean EDA were significantly different in the fearful versus neutral conditions, $t(19) = --2.47$, $p < .023$; $t(14) = 2.3$, $p < .04$, respectively.

Finally, we calculated the across-individual reliability scores, that is, interSC$_{EDA}$ and interSC$_{HR}$, for each neutral and emotional movie, and assessed its statistical likelihood using a nonparametric bootstrapping procedure (see Methods of Study 1 for details). These measures are presented in Table 2. As can be seen from the table, both emotional movies elicited highly reliable EDA and HR responses ($p < .01$ for all four interSC measures). The response reliability during neutral movies didn't approach significance ($p > .25$ for all four interSC measures).

The degree of interSC during emotional movies was associated with the intensity of emotional experience reported by the participants. As a next step, we assessed the relationship between the physiological measures and the emotional responses of the participants. As expected, positive movie was rated as positive (valence = 6.78, $SD = 0.9$) and arousing (arousal = 5.7, $SD = 1.45$), eliciting two distinctive positive emotions, that is, joy (6 ± 1.29) and amusement (5 ± 2.28). Negative movie was rated as negative (valence = 2, $SD = 1.84$) and arousing (arousal = 6.3, $SD = 1.3$), eliciting two distinctive negative emotions, that is, fear (6.17 ± 2.24) and anxiety (6 ± 1.74).

To assess the relationship between interSC and the subjective emotional experience, we computed rank correlations between the four subjective emotional responses and the individual measures of interSC for both movies and for both autonomic measures (interSC$_{EDA}$, interSC$_{HR}$). In addition, we computed a composite score (interSC$_{comp}$), by averaging the Fisher-transformed, z-normalized interSC$_{EDA}$ and the Fisher-transformed, z-normalized interSC$_{HR}$, obtained for each participant in each of the two movies. Correlations between interSC$_{comp}$ and the emotional responses are presented in Table 3 and in Figure 4. In a similar way, we also computed correlations between physiological reactivity scores and the emotional responses.

As can be seen from Table 3, while the interSC scores showed multiple significant correlations with subjective emotional responses (the interSC$_{comp}$ was significantly associated with all four emotional responses in negative movie and with two emotional

Table 3. *Pearson Correlations Between Physiological Measures and Emotional Responses*

	Positive movie				Negative movie			
	Valence	Arousal	Joy	Amusement	Valence	Arousal	Anxiety	Fear
interSC$_{HR}$	−.049	−.091	.217	**.583**	−.030	**.479**	**.394**	**.415**
p value	.421	.355	.186	.004	.455	.026	.05	.049
interSC$_{EDA}$	.136	.194	.368	**.690**	**−.522**	.266	**.557**	**.507**
p value	.329	.263	.108	.004	.016	.151	.010	.019
interSC$_{comp}$	.019	.088	**.354**	**.670**	**−.412**	**.571**	**.625**	**.648**
p value	.466	.348	.05	.000	.032	.003	.001	.001
HR reactivity	−.250	−.343	.002	.009	**−.648**	.129	.329	.220
p value	.205	.126	.498	.490	.001	.295	.078	.175
EDA reactivity	−.066	.247	−.393	−.043	−.06	.040	.27	.132
p value	.388	.140	.092	.444	.413	.444	.165	.320

Significant correlations (one-tailed) are marked in bold.

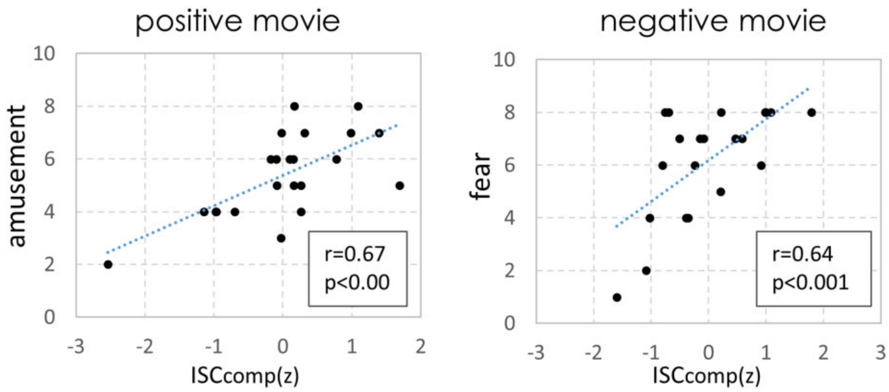

Figure 4. The association between individual emotional responses and interSC. InterSC_{comp} indexes the degree to which the variability of individual ANS activity was explained by the common (across-individuals) stimulus-locked component. As shown, the degree of individual physiological alignment with the stimulus-locked component was correlated with the intensity of subjective emotional responses to the movie.

responses in positive movie), only one of the reactivity scores reached significant correlation with emotional response.

Discussion

In Study 2, we directly assessed the relationship of the ANS response reliability (interSC) and the subjective emotional experience. We induced emotions by showing movie excerpts with neutral, positive, and negative emotional content. We found that (a) emotional movies but not neutral movies elicited reliable ANS responses, which were correlated across individuals; and (b) the degree to which individual's response time course correlated with the average, movie-driven component was strongly associated with the intensity of her emotional experience. Taken together, these results suggest that across-individual ANS response reliability is driven by the intensity of emotional experience, both at the group level and at the individual level.

In addition, we found that interSC measures better predicted individual emotional responses than the average reactivity scores. First, even after optimizing the time windows for emotional responses, the average reactivity scores were significant for negative movie and only marginally reached significance for positive movie, while interSC was highly significant for both movies. Second, while interSC_{comp} was associated with subjective emotional responses in both movies, almost none of the reactivity scores were associated with individual emotional responses.

General Discussion

The main thrust of the current research was to investigate whether ongoing ANS signals exhibit reliable, stimulus-locked temporal patterns in structured emotional context. We investigated the reliability of the ANS signals using the interSC approach, which quantifies the temporal alignment of response time courses across individuals. We found that a prolonged movie excerpt with mixed emotional content evoked time-locked ANS response patterns, which were correlated across individuals ($\text{interSC}_{EDA} = 0.41$; $\text{interSC}_{HR} = 0.34$). Similar results were obtained using shorter excerpts of movies containing specific emotional content (i.e., fearful and amusing). These results indicate that, despite the complex nature of the stimulation and the multitude of variance sources in ANS signals (Stemmler, 2004), a significant part of the autonomic response variability was driven by the dynamics of emotional stimulation.

In addition, we showed that the interSC of ANS responses is intricately linked to the intensity of emotional experience. In the first study (using a prolonged movie with mixed emotional scenes), we found that the interSC of ANS signals varied dramatically at different time periods of the movie, vacillating between very high (~ 0.7) to insignificant levels. Further investigation showed that periods of high interSC for both ANS measures coincided with periods of intense emotional experience as recalled by the subjects. A comparison of interSC dynamics to continuous subjective responses of emotional arousal supported this association. In the second study, we demonstrated that, while emotional movies elicited highly significant ANS response reliability, the neutral movies elicited ANS responses that were not consistent across individuals. Finally, we showed that individual differences in response reliability were strongly correlated with the intensity of subjective emotional responses. These results introduce a novel methodological approach as well as inform current theories of emotional processes.

Methodological Implications

The interSC approach introduced in this study indicates the degree to which the external stimulation "controls" the moment-by-moment changes in the ANS activity. Therefore, it allows for the investigation of stimulus-response effects, without compromising the temporal aspects of the ANS activity. We thus suggest that the interSC approach can serve as a methodological tool for studying the ANS responses and their dynamic characteristics during complex emotional experiences.

Notably, the results of the current study suggest that ANS response time courses combined with interSC approach can be used to investigate both stimulus-response group effects and individual response characteristics associated with emotional experiences. At the group level, we demonstrated that the stimulus-locked ANS component, which is shared across individuals, is highly reliable both in cardiovascular and in electrodermal measures. As such, it reflects consistent characteristics (such as intensity) of the emotional experience induced by the movie. In addition, it reflects response characteristics of the underlying physiological subsystems. For example, the phasic changes in the cardiovascular response time course temporally preceded the phasic changes in the electrodermal response time course (Figure 1a), reflecting differential response characteristics of these two ANS measures (Dawson, Schell, Filion, 1990; Kettunen et al., 1998).

At the individual level, we demonstrated that the degree to which the common component explained individual response variability (i.e., individual interSC) was strongly associated with the emotional effect of the movie on that individual (Figure 4). Notably, the interSC provided a better model for individual emotional responses than average reactivity scores. Previous studies that investigated temporal ANS response profiles in within-individual designs (Hsieh et al., 2010; Kettunen & Keltikangas-Järvinen, 2001; Kettunen et al., 1998; Mauss et al., 2005) emphasized the individual response characteristics (Kettunen et al., 1998; Sze, Gyurak, Yuan, & Levenson, 2010) and demonstrated the effects of emotions on within-individual response coherence (Mauss et al., 2005). We support and extend the previous studies by demonstrating that both within- and across-individual coherence measures can be used to assess consistent sources of variability in temporal ANS responses. Future studies combining these two approaches in specific experimental contexts can provide an in-depth characterization of the stimulus-specific responses, the individual characteristics affecting these responses, and the interaction between them (Stemmler, 2004; Stemmler & Wacker, 2010).

It should be noted that the interSC approach could be usefully applied in experimental situations that induce time-locked dynamic emotional changes, such as movies, narrated stories, or musical pieces. In contrast, experimental paradigms that do not induce a common component but distinctively affect each individual (e.g., mood inductions) will benefit from the within-individual coherence approach, but cannot rely on across-individual reliability methods. In addition, not all natural stimuli are equally efficient in evoking reliable ANS response patterns. For example, emotionally neutral movies, although providing structured perceptual input, do not evoke structured emotional experience, and thus elicit inconsistent ANS responses.

The psychophysiology research of emotions was one of the first fields to introduce emotional movies as powerful experimental manipulations (e.g., Gross & Levenson, 1995). Being driven by questions of ANS emotion specificity, studies mainly employed short movie excerpts targeting specific emotions, and characterized ANS response profiles associated with emotional peaks. However, as emotions evolve in time and in context (Barrett, 2006; Lewis, 2005; Scherer, 2009), studying the dynamic changes of ANS activity can significantly contribute to the research of emotional experience. The broad methodological implication of the current study lies in the demonstration that moment-to-moment changes of the ANS activity bear reliable and meaningful information, which can be systematically studied in across-individual designs. The response reliability approach thus provides a complementary tool to the traditionally employed reactivity scores to study naturally occurring, dynamic emotional experiences.

Response Coherence during Emotional Experiences

It has been previously proposed that one of the key characteristics of emotions is to facilitate coherence across and within various response systems (e.g., Ekman, 1992; Frijda, Ortony, Sonnemans, & Clore, 1992; Lazarus, 1991; Levenson, 1994; Scherer, 1984; Tomkins, 1962). Indeed, several studies have shown that intense emotional experiences lead to enhanced response coherence in the ANS (e.g., Mauss et al., 2005), as well as in the CNS (e.g., Raz et al., 2012). The current study supports and extends this view. We showed that emotional arousal leads to increased response coherence not only within (intraSC) individuals but also across individuals (interSC). These results are in line with a recent brain imaging study, which showed that emotional arousal enhanced the across-individual synchronization of widespread brain activity (Nummenmaa et al., 2012). Taken together, this evidence demonstrates that emotional experiences lead to organized physiological responses, which are correlated both within and across individuals. The functional role of such within- and across-individual alignment is outside the scope of the current article, and thus is not discussed here in detail. We note, however, that several recent works discussed the social effects of physiological response alignment across individuals, suggesting that it serves as a biological mechanism for promoting shared interpersonal states (Hasson, Ghazanfar, Galantucci, Garrod, & Keysers, 2012; Helm, Sbarra, & Ferrer, 2012; Nummenmaa et al., 2012). In the context of this framework, the demonstrated enhancement of ANS response coherence has intriguing implications for the role that emotions play in social interactions.

Reliability of CNS and ANS Activity during Dynamic Complex Stimulation

The interSC approach has been introduced and applied in a series of imaging studies that have investigated the reliability of brain activity evoked by naturalistic stimuli, such as prolonged complex movies and narrated stories (Golland et al., 2006; Hasson et al., 2004; Honey, Thompson, Lerner, & Hasson, 2012; Lerner, Honey, Silbert, & Hasson, 2011; Nummenmaa et al., 2012). These studies have shown that, despite the uncontrolled nature of the task and the complexity of the stimuli, naturalistic stimulation evoked highly reliable and functionally specific response patterns in a variety of brain regions (Hasson & Honey, 2012; Hasson, Malach, & Heeger, 2010).

Despite the complexity of ANS-CNS interactions, operating in multiple time scales and involving recursive feedback circuits (e.g., Benarroch, 1993; Jänig & Häbler, 2000; Jänig & McLachlan, 1992a, 1992b; Thayer & Lane, 2000), we demonstrated reliable temporal responses to naturalistic stimulation in the downstream autonomic systems. These results support the current views that the ANS and CNS interact in a coordinated fashion (Benarroch, 1993; Damasio, 1998; Thayer & Lane, 2000), together forming a complex biobehavioral system for adaptive responses to environmental demands (e.g., Bradley & Lang, 2000; Hilton, 1982; Hilton & Hilton, 1975; Thayer & Lane, 2000). Further investigation, targeting the temporal characteristics of the CNS and ANS response time courses, could significantly contribute to the understanding of the complex cascade of information processing implicated in dynamic emotional experiences.

Summary

In this study, we investigated the reliability of continuous ANS signals and their intricate relationship to subjective emotional experiences. We demonstrated that continuous ANS signals combined with across-individual measures, such as interSC, can be used to study the dynamic characteristics of emotional experiences. The approach presented in the current study allows for systematic investigation of (a) naturally occurring emotional experiences, elicited by dynamic naturalistic stimuli; (b) temporal profiles of the ANS responses during emotional experiences; and (c) factors that affect the emotion-related ANS responses, including both stimulus-response and individual response characteristics.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web-site:

Figure S1: Reliability of electrodermal and cardiovascular activity.
Figure S2: Computing response reliability and its dynamics: A working example.