Physiological Synchronization Is Associated with Narrative Emotionality and Subsequent Behavioral Response

Bethany K. Bracken[1,*], Veronika Alexander[2,*], Paul J. Zak[2],
Victoria Romero[1], and Jorge A. Barraza[2]

[1] Charles River Analytics, Inc., Cambridge, MA
[2] Claremont Graduate University, Center for Neuroeconomics Studies, Claremont, CA
`{bbracken,vromero}@cra.com,`
`{veronika,paul}@neuroeconomicstudies.org,`
`jorge.barraza@cgu.edu`

Abstract. Neurophysiological compliance is a correlation of neurophysiological measures (synchronicity) between individuals. Higher compliance among team members is related to better performance, and higher synchronicity occurs during emotional moments of a stimulus. The aim of the current study is to examine whether synchrony may be observable via peripheral nervous system (PNS) activity. We used inter-subject correlation (ISC) analysis to assess whether synchronicity of PNS measures are related to stimulus emotionality or similarity in behavioral responses. Participants viewed a 100-second emotional video, followed by an appeal to donate experimental earnings to a related charity. We found high ISC for cardiac and electrodermal activity (EDA) between donors versus non-donors. For both groups, we found an association between ISC of cardiac activity and emotional moments in the stimulus. For non-donors we found an association between ISC of EDA and emotional moments. Our findings indicate that PNS measures yield similar results to neurophysiological measures.

Keywords: Cognitive Modeling, Perception, Emotion, and Interaction, Physiological Synchronization, Inter-Subject Correlation Analysis, RR-Interval, Skin Conductance Level, Narrative.

1 Introduction

Neurophysiological compliance is defined as joint neurophysiological changes in two or more people engaged in the same activity or as a positive correlation between neurophysiological measures between team members [1, 2]. For instance, an electroencephalography (EEG) study found that during a social interaction, both individuals will continually adapt their own behavior to mirror that of the other, and this state of interactional synchrony correlates with interbrain synchronization in the alpha-mu band

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[*] Co-First Authors.

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between right centro-prietal regions [3]. Likewise, in simultaneously recorded pairs of musicians, increased synchronization in EEG signals (most strongly in fronto-temporal locations) were found to be coordinated both during the playing and preparation period (metronome tempo setting) [4]. A functional near-infrared spectroscopy (fNIRS) study found that coordination of simple behaviors like finger tapping show increased coherence activity in the premotor cortices of the paired participants [5]. Even unconsciously modulated behaviors like fingertip movements, when synchronized, are correlated with an increase in synchronization in cortical regions of the individuals [6].

Although all of these studies included paired recordings of individuals taking part in a joint activity in real time, neurophysiological correlation also appears to occur when participants are not simultaneously observed. Hasson et al. [7] used functional magnetic resonance imaging (fMRI) to assess spatiotemporal activity patterns in the brains of participants freely viewing an unedited movie (The Good, The Bad, and The Ugly starring Clint Eastwood, 1966 Alberto Grimaldi Productions S.A. All Rights Reserved). Each participant was recorded during a separate experimental session. Even during cross-session stimulus exposure during which participants could attend to any area of the visual field, participants showed significant voxel-by-voxel synchronization in association cortices as well as primary and secondary visual and auditory areas. Inter-subject correlation was the most pronounced during emotionally arousing scenes (e.g., gunshots, explosions, and surprising plot twists). In a similar study, Dmochowski et al. [8] used EEG to capture the fast oscillatory responses (down to a single second, which are invisible to fMRI) while individuals viewed short film clips (e.g., during close ups of a child playing with a loaded gun in Bang! You're Dead, a TV episode from Alfred Hitchcock Presents, Season 1, 1961). They found that peak correlations in neural activity corresponded to moments in the film that were highly tense, suspenseful, or surprising. In particular, they found increased power in the frontal theta component (linked to encoding of new information [9, 10]), and reduced power in the temporal beta component (linked to sustained monitoring of external emotional stimuli [11]). This correlation was lost when film clips were scrambled [8], indicating that synchrony is dependent on the temporal coherence of the stimulus.

The aim of the current study is to examine whether synchrony may be observable via peripheral neural activity. EEG [12], fNIRS [13], and fMRI are cumbersome and complicated to use, and may distract from task performance. Fortunately, biometric techniques for sensing peripheral nervous system indicators (e.g., heart rate, and skin conductance) provide an alternative means of assessing physiological synchronicity. For instance, as far back as the 1950's, studies have indicated that physiology covaries in therapists and clients over the course of a counseling session [14]. Later, physiological compliance was found to correlate with how much a couple "liked" one another [15], and even accounted for some of the variance in marital satisfaction [16]. More recently, it has been shown that physiological compliance occurs even in college students assigned randomly to a position on a team during a process control simulation [1]. Team performance on a complex and dynamic task (monitoring a chemical plant to maintain safe operating conditions during maximum output conditions) could be predicted by combining measures of sympathetic and parasympathetic nervous system activity (with an electrocardiogram (ECG) and an impedance cardiogram (ICG)), accounting for 10% of the variance in performance scores .

In the current analysis, we assessed whether inter-individual synchronicity of peripheral nervous system measures (RR-interval (the amount of time between the same phase of the heartbeat) and skin conductance level (SCL)) are also related to emotionality of the video or to similarity in behavioral response. To assess inter-individual synchronicity, we adapted a previously unused statistical approach taken in fMRI and EEG research [7-11] for peripheral nervous system measures. In the current study, participants were presented with a narrative of a father talking about his two-year old son who has terminal cancer. At the end of the video, participants were presented with an opportunity to donate some of their experimental earnings to a charity tied to the narrative. We previously found that increases in parasympathetic tone were different in donors versus non-donors at a trend level (p=0.07), and that the baseline-corrected RR-interval during narrative presentation predicts who will make a donation [17].

2 Materials and Methods

2.1 Participants and Procedure

We recruited 163 participants (68 female) from Claremont colleges and the surrounding community through mass e-mails, posted fliers, and an existing online recruitment pool (average age = 20.91 ± 5.20). Sixty-four percent of participants self-identified as Caucasian, 4% as Latino, 17% as Asian, 4% as African American, and 11% as "other." Participant payments varied between $20-$40 USD, depending on correctly answering questions about the narrative (average = $37.53, $33.79 after voluntary donations). Study sessions were conducted at the Center for Neuroeconomics Studies at Claremont Graduate University in Claremont, CA. Claremont Graduate University's Institutional Review Board and the U.S. Army Medical Research and Materiel Command's Office of Research Protections, Human Research Protection Office approved the study.

After informed consent, participants were fitted with physiological sensors. Participants then completed a questionnaire that included demographics and a number of state and trait measures. They were then seated privately in a dimly LED lit room approximately 2 feet in front of a 15 inch Macbook Pro laptop (Apple, Inc.) equipped with headphones. Participants viewed stimuli in isolation, rather than together as a team of individuals, similar to other studies [7]. All tasks, including the donation task, were presented in MATLAB® (Mathworks, Inc.), using the Psychophysics Toolbox extensions [18]. After a five-minute baseline data acquisition period for autonomic nervous system (ANS) measures, participants viewed the narrative video stimulus. Peripheral nervous system measurement was recorded throughout the stimulus.

Participants next rated their emotions by answering five questions related to the narrative, with a possible $5 USD per correct question to add to the $15 USD base participation payment. Finally, participants were given a brief description of a charity that serves an issue aligned with the prior narrative, reminded of their anonymity, and given the option to donate none, some, or all of their participation earnings to the charity. Once complete, participants were asked to write down their final earnings on a payment slip and paid their total earning in private. There was no deception of any kind in this study.

2.2 Narrative Stimulus

The narrative during which data in the current study were collected was an edited story obtained from St. Jude's Children's Research Hospital of a father who has a 2-year old son who is dying of brain cancer ("Ben's Story;" run time: 100 sec, audio/video). The video was obtained, and used by permission, from St. Jude's Children's hospital, and has been used in prior studies investigating physiology and emotion [19]. After viewing this video, participants were offered the opportunity to donate some of their study earnings to St. Jude's. Roughly 52% made a donation to the charity after the narrative, with an average donation of $6.94 (SD = $6.99).

2.3 Autonomic Measures

To measure cardiac and respiratory activity, participants were fitted with three disposable Ag-AgCl electrocardiogram (ECG) electrodes using a Lead III configuration. ECG and respiration band signals were wirelessly relayed to a Biopac MP150 data acquisition system using BioNomadix® transmitters. Data were recorded at a sampling rate of 1 kHz using AcqKnowledge® software version 4.2 (BIOPAC Inc., Goleta, California).

2.4 Analyses

Following data collection, skin conductance waveforms were visually inspected for brief periods of signal loss, and data drop-offs shorter than 1 second in length were replaced with averages from adjacent parts of the waveform. Additionally, waveform noise due to experimenter-noted movement was smoothed using mean-value replacement from adjacent parts of the waveform. Next, a 10-Hz low-pass filter was applied to the waveform to remove high-frequency noise [20], and a square root transformation was applied to adjust for skew inherent to skin conductance data [21, 22]. After transformations, average skin conductance level (SCL) was extracted for the final 2 min of the baseline and for the 100 second time-span of the narrative. These values were used to calculate percent change in SCL from baseline to the narrative. For synchrony analyses, 1-second segments of SCL and RR-intervals were taken from baseline and narrative stimulus. ECG waveforms were manually inspected for artifact removal. A band-pass finite impulse response (FIR) filter was applied to remove both high- and low-frequency noise, followed by smoothing. RR-intervals were extracted from AcqKnowledge.

We separated data into groups of donors and non-donors, based on whether any monetary donation was made, and conducted an inter-subject correlation (ISC) analysis similar to Hasson et al. [7]. Data were baseline corrected using accumulated average of physiological data during video and then separated into 5-second epochs. ISC analysis steps include: (1) calculation of pairwise correlations for the two groups, (2) calculation of the mean pairwise correlation coefficient, (3) use of false discovery rate based upon multiple comparison correction, (4) test of significance of ISC from zero, and (5) test of between-group significance. All analyses were conducted using Visual Basic for Applications (Microsoft®) and Stata (Stata Corp®).

3 Results

We examined two separate physiological measures, RR-interval (the amount of time between the same phase of the heartbeat) and skin conductance level (SCL).

3.1 RR-Interval

Emotionality. We first assessed whether inter-subject correlation (ISC) during narrative viewing had any relation to emotionality of the video. We included a 5-second delay between stimulus viewing and stimulus response for cardiac data in our analysis in order to account for the lag between stimulus onset and the event-related physiological response. Based on the data fit, we found 5-seconds to be the optimal temporal lag for viewed narratives [17]. The video was rated by a separate group (N=45) who were asked every five seconds during the video presentation how much concern they were feeling at that time. We found that over the entire video the RR-interval ISC for both donors and non-donors was correlated with previously obtained emotional ratings ($r=0.64$, $p<0.01$).

Within-Group Correlations. Next, we conducted ISC analysis on RR-interval data separated into five second epochs for each group separately (donors vs. non-donors). Note that although the video is 100 seconds long, we lost three seconds due to interpolation of RR-interval data (see Fig. 1). All non-zero r-values are significant to $p<0.01$. Within both groups, members showed correlated physiological responses at the beginning of the video (starting during the 16-20 second epoch during the first close-up of the marks and scars on Ben's head). Participants classified as non-donors exhibited synchronous physiological responses early in the narrative, but became unsynchronized by the middle of the video. Within the non-donor group, ISC was significant ($p<0.01$) for epochs between seconds 16-35 (during the entire period of Ben's close-up until the camera cuts away again to the father) and between seconds 41-80 (during the father's monologue in which his voice begins to shake, until the camera again cuts to Ben). Those in our donor group, however, remained synchronous as the video progressed. For the donor group, ISC was significant for all epochs after second 16. The peak ISC occurred early in the video for the non-donor group ($r=0.52$ during the 41-45 second epoch), but later in the video for the donor group ($r=0.28$ during the 66-70 second epoch).

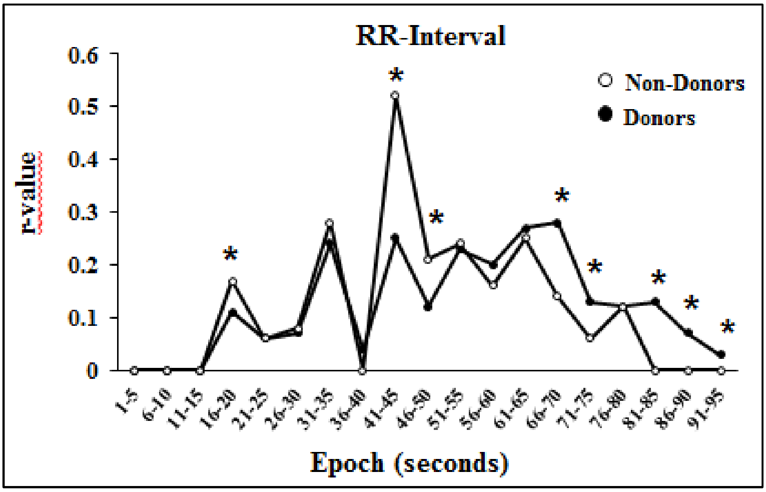

Fig. 1. Within- and between-group ISC analysis results of SCL data. All non-zero correlations are significant to p<0.01. Significant between-group differences are labeled with an asterisk (*=p<0.01).

Between-Group Correlations. Finally, we tested to see when the donor group differed from the non-donor group. In Fig. 1 all between-group differences are marked with an asterisk (*=p<0.01). Although RR-interval ISC for all participants, regardless of group, was correlated at the beginning of the video, this may have been due to variability within both groups. The two groups were different from each other during the 16-20 second epoch (Ben's first close-up; 2-tailed p=0.0082), however, ISC between the groups was not significantly different again until the 36-40 second epoch (the point at which the viewer learns that Ben is still in danger, despite his healthy appearance). This difference in ISC between groups remained significant for the next ten seconds, and then became non-significant again from second 66 until the end of the video, with the exception of the 76-80 second epoch.

3.2 Skin Conductance Level

Emotionality. For SCL data, we again assessed whether ISC during narrative viewing had any relation to emotionality of the video. We found that, unlike RR-interval findings, the two groups differed in the correlation of SCL ISC with emotional ratings (donor p=0.48; non-donors r= 0.52, p=0.02).

Within-Group Correlations. We next conducted ISC analysis on data separated into five-second epochs for donors versus non-donors (see Fig. 2). All non-zero r-values are significant to p<0.01. In contrast to results obtained during examination of the RR-interval data, we found that SCL showed high ISC during the entire video for both groups. Further, SCL for those who later chose not to donate were more highly correlated with each other than those who did donate to charity. Correlation values above 0.20 were reached during only six of the 20 epochs for the donator group, but were reached during 16 of the 20 second epochs for the non-donator group. The peak ISC value for the donor group only reached r=0.30 (during 91-95 second epoch when the father says he is going to put his smile on too, and keep going with his son until his son takes his last breath). However, the peak ISC for the non-donating group reached 0.47 during the 61-65 second epoch, and remained there for another five seconds, during the time when the father is seen reading a book to Ben and his voice is breaking saying "There are no words.").

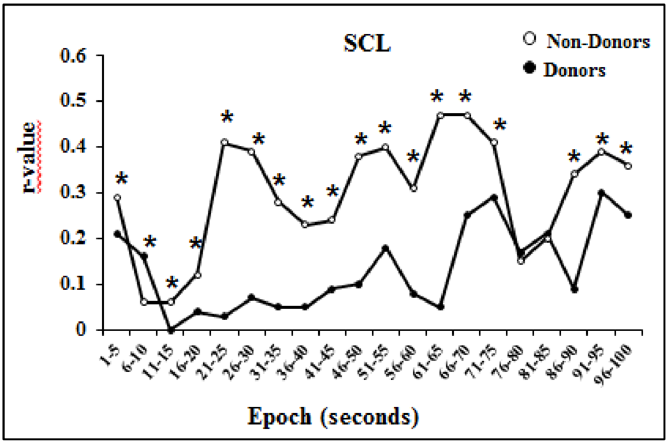

Fig. 2. Within- and between-group ISC analysis results of RR-interval data. All non-zero correlations are significant to p<0.01. Significant between-group differences are labeled with an asterisk (*=p<0.01).

Between-Group Correlations. Finally, we tested to see when the donor group differed from the non-donor group (see Fig. 2). Again, in contrast to our findings on RR-interval data, ISC was significantly different between the groups during all but ten seconds of the video (epochs containing seconds 76-85—a close-up of Ben's smiling face).

3.3 Variability in the Physiology across Groups

The discrepancy in results for RR-interval and SCL prompted us to look more closely at the data to determine what might be underlying these results (see Fig. 3). We found that for both donors and non-donors, the percent change in RR-interval from baseline increased over the entire time-course of the video. However, for non-donors the percent change in SCL from baseline increased during the first few seconds of the video, then decreased throughout the remaining viewing period. For donors the percent change in SCL from baseline showed a similar increase during the first few seconds of the video, but then remained stable across the remaining viewing period.

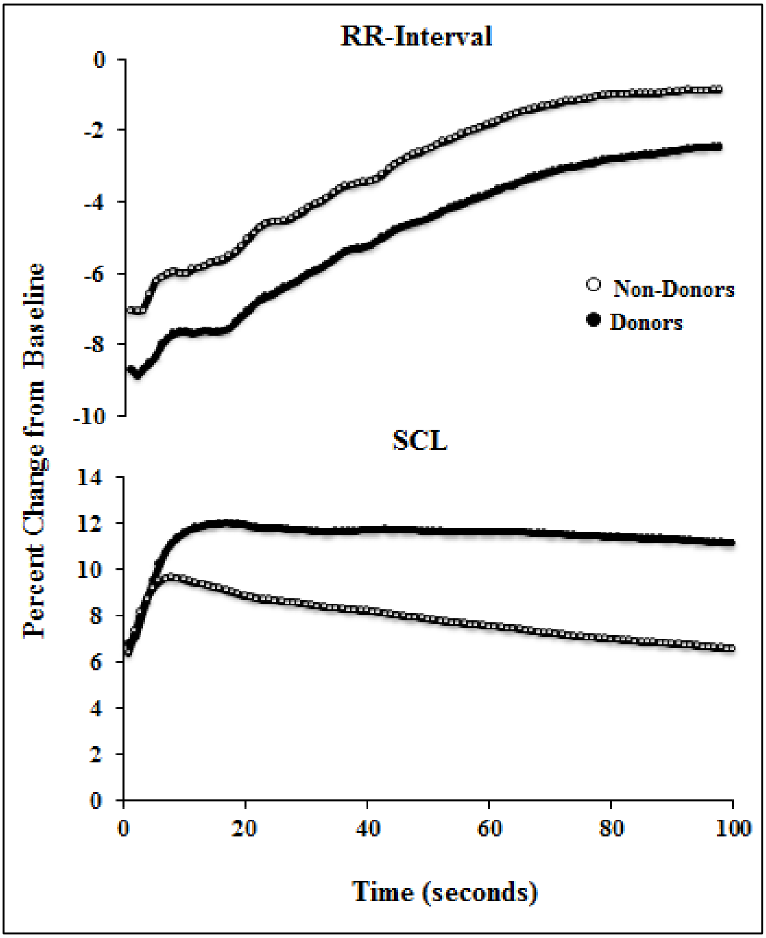

Fig. 3. Accumulated average percent change from baseline to stimulus

4 Discussion

Our paper provides evidence for the use of inter-subject correlation as a measure of peripheral nervous system (PNS) synchrony. These results, reported herein, have several implications. First, our RR-interval (the amount of time between the same phase of the heartbeat) synchrony findings were similar to those of Hasson et al. [7]. Participants in both groups exhibited synchronous physiological responses that correlated with moments in the stimulus that were previously rated as highly emotional. This is true even when participants were freely viewing videos in separate sessions. Interestingly, during the Hasson et al. study, participants were tested three weeks after movie viewing for memory of events occurring within the film clip [23]. In that study, enhanced ISC correlated with better episodic memory. Future studies will be needed to assess whether this extends to peripherally measured physiological indicators as well.

Second, similar to studies assessing inter-group synchronicity in relation to task performance, our between-group analysis indicates that participants who behaved similarly exhibited highly correlated physiological responses. For RR-interval data, individuals in the donor group showed synchronous responses during 84% of the narrative presentation (16 of 19 epochs), while individuals in the non-donor group showed synchronous responses for 63% of the narrative (12 of 19 epochs). This finding was even more pronounced for skin conductance level (SCL), with individuals in the donor group showing synchronous responses during 95% of the narrative, and individuals in the non-donor group showing synchronous responses for 100% of the narrative.

However, RR-interval did not consistently distinguish between the donor and non-donor groups. For instance, the percent change from baseline of the RR-interval was quite similar in both groups, and there was a correlation with emotionality of the stimulus for both groups. This indicates that even though only 52% of participants chose to donate (84/163), all participants were emotionally affected by the narrative. In contrast, the percent change from baseline of SCL, which, after an initial increase in both groups, remained static for those who eventually chose to donate, but decreased in those who did not donate. However, the correlation with emotionality of the stimulus (a correlation in non-donors, but no correlation in donors) indicates that a change in SCL from baseline after the initial response may not be related to emotion. Further study will be needed to clarify the relationship between emotional response and the likelihood of the choice to donate.

Kreibig and colleagues examined physiological response patterns to neutral versus fear- and sadness-inducing films, and found that SCL was significantly different in the fearful versus neutral [24]. In addition, the rate of non-specific skin conductance response (the number of supra-threshold (0.025μS) increases of skin conductance level per minute) was significantly different in both the fearful versus neutral contrast and the sad versus neutral contrast. Although they did not analyze RR-interval results directly, they used RR-interval to calculate heart rate and respiratory sinus arrhythmia. Heart rate was significantly different in the fearful versus sad contrast, but respiratory sinus arrhythmia was not significant in any contrast [24]. This paper also included a thorough literature review on peripheral physiological responding during emotion-induction paradigms. Of the literature they reviewed, three papers showed increased SCL during sadness, four showed decreased SCL during sadness, and one showed no change in SCL. Although again they did not report on RR-interval directly, they did report on heart rate variability (HRV), the variability of the RR-interval. Two papers showed increased heart rate variability during sadness, one paper showed decreased HRV during sadness, and five papers showed no change in HRV during sadness [24]. Our results add to this literature by providing a new measure to examine the role of physiology and emotionality. Future research should test whether emotional valence influences synchrony patterns (e.g., whether synchrony is more prevalent for positive versus negative emotions).

In summary, the current study provides evidence that synchrony can be quantified in peripheral physiology, including RR-interval and SCL. Similar to fMRI, fNIRS, and EEG measures assessed in previous studies, both peripheral measures of ISC were associated with the emotionality of a stimulus and to behavioral outcomes related to the stimulus experience during physiological recording. This work adds to the growing body of literature suggesting that measurements taken peripherally yield similar results to those acquired with more complicated neurophysiological techniques, and demonstrates the successful adaptation of inter-subject correlation analysis to peripheral nervous system measures.

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