

Networks of Brain-Heart Interactions During Elicited Emotional States

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Abstract

Understanding brain-heart interactions (BHI) is essential to understanding the emotional and physiological complexities associated with emotional granularity. This study examined the network physiology in terms of BHI as well as the associations of distinct brain regions and frequency bands in various affective states. BHI was evaluated utilizing the controlled time-delay stability (cTDS) method. The statistical analysis revealed significant differences between brain-to-heart and heart-to-brain networks (P -values < 0.0001), with heart-to-brain networks having stronger connections across emotional states, indicating the important role the heart plays in influencing brain activity associated with arousal and valence. Higher frequency bands exhibited stronger network connections, indicating their applicability to the BHI in this context. Notably, the networks representing various emotional states displayed symmetrical distributions of average link strength across brain regions. The research indicates that cTDS is a useful instrument for investigating BHI coupling and network interactions, emphasizing the importance of considering the directionality of the brain-heart connection under distinct emotional conditions, including differences in levels of arousal and valence.

1. Introduction

The autonomic nervous system, comprising the sympathetic and parasympathetic branches, modulates the rhythmic activity of the heart, which in turn can be a function of brain activity [1]. Analogously, the cardiovascular system exhibits cardiac rhythm changes characterized by ongoing fluctuations and nonlinear, scale-invariant temporal dynamics. However, the specific mechanisms by which the brain and heart dynamically interact and coordinate to generate distinct responses remain unclear [2]. The precise implications of brain rhythms and their temporal dynamics in facilitating

communication between the brain and the heart are still not fully understood. The investigation of brain-heart interactions (BHI) poses significant challenges due to the intricate nature of the underlying mechanisms involved [3]. Recent research has shed light on the bi-directional relationship between the brain and heart, indicating possible changes in connectivity strength and directionality depending on emotional state. While the brain has long been recognized as the body's control center, it has become increasingly apparent that the heart has considerable influence over brain function and overall well-being. This reciprocal influence between the brain and the heart has raised fundamental questions about the causal relationship between the brain and the heart and under what circumstances – be it physical, cognitive, or emotional the bi-directional coupling directionality changes [4].

Prior research has established the utilization of the time-delay stability (TDS) concept in the analysis of the communication between the cardiac system and the brain via brain rhythms and the transition across sleep stages [3], [5]. By concurrently examining cardiac signals and brain activity, this work aimed to further examine the bi-directional pathways connecting these two systems by applying a controlled TDS (cTDS) to biosignals obtained from the DEAP database [6]. Furthermore, it aimed to investigate the participation of distinct cerebral regions and frequency ranges in various emotional responses from electroencephalogram (EEG) recordings.

2. Experimental Method

2.1. Data

The Database for Emotion Analysis using Physiological signals (DEAP) is an openly available dataset that consists of recordings of EEG and peripheral physiological signals obtained from a total of 32 individuals [7]. The data collection involved capturing participant recordings during observation of a series of 40 music videos, each lasting one minute, which were specifically created to evoke

diverse emotional reactions. The participants assigned ratings to each video, evaluating them on categories of arousal, valence, likeability, dominance, and familiarity. In the present study, only the arousal and valence evaluations were employed, both of which were quantified as numerical values ranging from 1 to 9 and assessed as high (H), low (L), arousal (A), or valence (V). The EEG data was preprocessed, including down-sampling to a frequency of 128 Hz, removing artifacts induced by eye movements, applying band-pass frequency filtering, and reordering the EEG channels prior to extracting EEG frequency bands for further analysis. Comparatively, the plethysmograph (PPG) signals were subjected to similar preprocessing processes. In this work, eight EEG channels were selected to represent the frontal, central, temporal, and occipital lobes of the cortex (Fp1, Fp2, C3, C4, O1, O2, T7, & T8). Four separate brain rhythms were derived from each channel, namely theta (4-7 Hz), alpha (8-12 Hz), beta (13-29 Hz), and gamma (30-45 Hz).

2.2. Controlled Time-Delay Stability

The cTDS algorithm estimates the interactions between node pairs of the physiological features by assessing the controlled time delay of the directed interactions while adjusting for the indirect interactions. The cTDS algorithm separates directional links between node pairs to differentiate direct and indirect connections while accounting for other nodes. This differentiation isolates directional links between each pair of systems and controls for nearby nodes. Thus, cTDS can precisely characterize delay and direction for each link without secondary paths involving other nodes confounding the results [6].

2.3. Averaging Procedure for Assessing Links Strength

Outliers that occur in physiological network link strength assessment result from artifacts and differ between individuals. Calculating the distribution and standard deviation of cTDS values from all group subjects for each pair of physiological data in a network link accounts for inter-subject variability. Subjects with link %cTDS scores above the group average plus two standard deviations were therefore excluded from the analysis, while the rest is used to determine the link average [2].

3. Results & Discussion

3.1. Brain-to-Heart (BHI) v. Heart-to-Brain Interactions (HBI)

This section presents initial findings on the interaction between brain and heart activities, examining brain-to-heart

(BHI) and heart-to-brain (HBI) connections. Radar charts illustrate the coupling strength between individual EEG electrodes and heart activity across different frequency bands and affective states. The size of the octagonal shapes reflects the overall strength of connections within the networks (Figure 1). Symmetrical patterns reveal relatively uniform link strength across all EEG electrodes within each network, with no single electrode exhibiting significant dominance. This visual representation reflects consistent behavioral symmetry, with variations in magnitude across different frequency bands, as we assess the average link strength across various EEG electrode locations in the HAHV, LAHV, HALV, and LALV networks.

ANOVA testing showed significant differences between BHI and HBI networks (P -values < 0.0001). The data consistently showed a trend toward subdued connectivity within the BHI pathway, highlighting the heart's robust influence on brain activity as reflected in HBI values. These consistent findings underscore that HBI consistently exhibits stronger interactions across all frequency bands compared to BHI. This underscores the heart's substantial role in emotional regulation and overall well-being, suggesting that brain-to-heart and heart-to-brain networks process and respond to affective states differently. These distinctions emphasize the importance of considering directionality in BHI investigations. Previous research has shown that sympathovagal activity plays a central role in initiating the affective response. Ascending modulations in vagal activity precede changes in brain dynamics and correlate with reported arousal levels. Our findings support this by indicating a stronger coupling for the heart-to-brain interaction in the current paradigm [4], [8].

3.2. Influence of Frequency Sub-bands on BHI & HBI

Additionally, this work examined the influence of different EEG frequency bands on BHI and HBI networks. A discrepancy in the individual impact of EEG rhythms on both of them was evident (Figure 1). To examine these differences, an ANOVA test was conducted, revealing statistically significant variations in link strength between the four frequency bands across various affective states within both networks. It is noteworthy that these variations were more pronounced within the heart-to-brain network (P -values $< 10^{-12}$). In all emotion states, theta and alpha frequencies dominated the network (Figure 1). Upon closer examination, we found that the heart's modulation of brain activity was most pronounced, particularly within higher-frequency bands. Prior EEG studies provided insights into relationships between frequency band oscillations and emotion processing. Beta and

gamma frequencies indicated rapid unpleasant stimulus processing [9] while higher frequency bands better identified emotions [10]. Our investigation revealed that high-valence conditions profoundly influenced the interactions, supporting prior research linking EEG band activities to cardiac response and emotional stimuli. This underscores the complex interplay of frequency bands, emotional valence, and physiological responses [11].

3.3. Differentiation Between Emotions

For the heart-to-brain networks across different frequency bands, no statistically significant differences were observed. However, for the brain-to-heart network, a trend was apparent for the theta and beta EEG bands within the range of $0.05 < p \leq 0.1$ (Table 1). Consequently, it may be necessary to conduct further investigation and consider alternative features to reflect the behaviors of the brain and heart, such as heart rate variability, in order to effectively differentiate between emotions and include other tasks such as attention [12], [6].

Table 1. P-values obtained from the ANOVA test for assessing significant differences between emotion states in the Brain-to-Heart and Heart-to-Brain networks with respect to frequency bands.

	Theta	Alpha	Beta	Gamma
Brain-to-Heart	0.08	0.25	0.06	0.11
Heart-to-Brain	0.89	0.42	0.95	0.65

4. Conclusion

The study explores the complex BHI and its significance in understanding emotional intricacies. Using the cTDS approach, the study found significant findings on BHI dynamics, emphasizing its directionality, especially in emotional states with variations in arousal and valence. Theta and alpha frequency bands were found to mediate BHI, underscoring their importance in emotional reactions. This research contributes to understanding the bi-directional interaction between the brain and the heart, providing insights into emotional regulation. Future research may explore alternative characteristics to better distinguish between different emotional states.

Acknowledgments

This work was supported by the Healthcare Engineering Innovation Center (HEIC) at Khalifa University, Abu Dhabi, UAE.

References

- [1] Silvani A, Calandra-Buonaura G, Dampney RA, Cortelli P. Brain–heart interactions: physiology and clinical implications. *Philosophical Transactions of the Royal Society A Mathematical Physical and Engineering Sciences* 2016;374(2067):20150181.
- [2] Ivanov PC, Wang JWJL, Zhang X, Chen B. The New Frontier of Network Physiology: Emerging Physiologic States in Health and Disease from Integrated Organ Network Interactions. Springer International Publishing, 2021; 237–254.
- [3] Lin A, Liu KK, Bartsch RP, Ivanov PC. Delay-correlation landscape reveals characteristic time delays of brain rhythms and heart interactions. *Philosophical Transactions of the Royal Society A Mathematical Physical and Engineering Sciences* 2016;374(2067):20150182.
- [4] Candia-Rivera D. Brain-heart interactions in the neurobiology of consciousness. *Current Research in Neurobiology* 2022;100050.
- [5] Bartsch RP, Liu KK, Bashan A, Ivanov PC. Network physiology: how organ systems dynamically interact. *PLoS one* 2015;10(11):e0142143.
- [6] Marzbanrad F, Yaghmaie N, Jelinek HF. A framework to quantify controlled directed interactions in network physiology applied to cognitive function assessment. *Scientific Reports* 2020;10(1):18505.
- [7] Koelstra S, Muhl C, Soleymani M, Lee JS, Yazdani A, Ebrahimi T, Pun T, Nijholt A, Patras I. Deap: A database for emotion analysis; using physiological signals. *IEEE transactions on affective computing* 2011;3(1):18–31.
- [8] Luft CDB, Bhattacharya J. Aroused with heart: Modulation of heartbeat evoked potential by arousal induction and its oscillatory correlates. *Scientific reports* 2015;5(1):15717.
- [9] Li Y, Cao D, Wei L, Tang Y, Wang J. Abnormal functional connectivity of eeg gamma band in patients with depression during emotional face processing. *Clinical neurophysiology* 2015;126(11):2078–2089.
- [10] Wei C, Chen LI, Song Zz, Lou Xg, Li Dd. Eeg-based emotion recognition using simple recurrent units network and ensemble learning. *Biomedical Signal Processing and Control* 2020;58:101756.
- [11] Mishra S, Srinivasan N, Tiwary US. Cardiac–brain dynamics depend on context familiarity and their interaction predicts experience of emotional arousal. *Brain Sciences* 2022;12(6):702.
- [12] Mather M, Thayer JF. How heart rate variability affects emotion regulation brain networks. *Current opinion in behavioral sciences* 2018;19:98–104.

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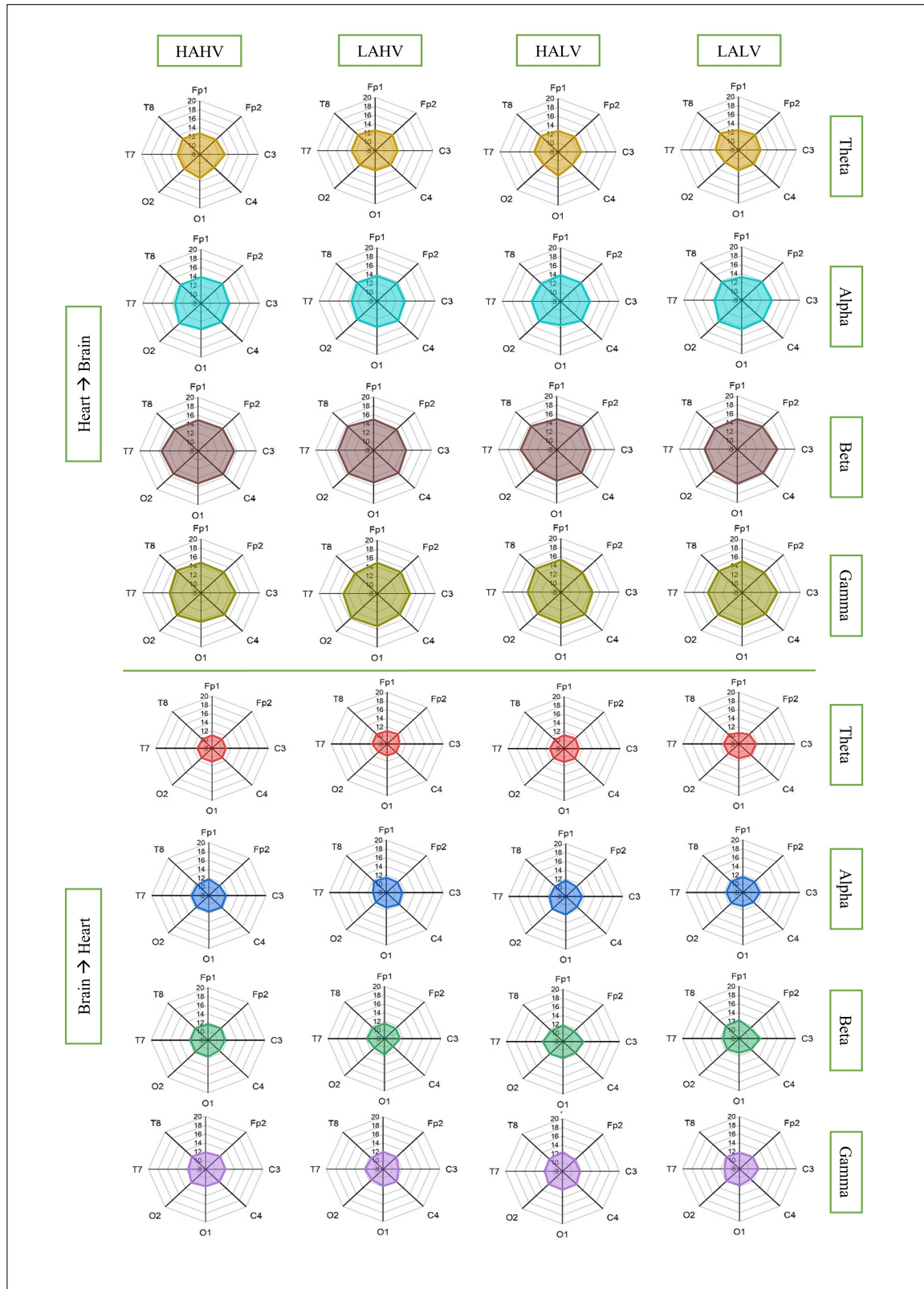


Figure 1. Brain areas are represented by Frontal (Fp1 & Fp2), Central (C3 & C4), Occipital (O1 & O2), & Temporal (T7 & T8) EEG channels. Radar-charts centered in each polygon represent the relative contribution of brain control from different brain areas to the strength of network links during different emotion states. The length of each segment along each radius in the radar-charts represents cTDS coupling strength between the heart and each EEG channel location in the specified frequency band.