EFFECTS OF ATTACHMENT STYLES ON PREFRONTAL CORTEX DURING NATURALISTIC SOCIAL INTERACTION: AN FNIRS BASED HYPERSCANNING STUDY

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BURCU YARGIÇOĞLU

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submitted by **BURCU YARGIÇOĞLU** in partial fulfillment of the requirements for the degree of **Doctor of Philosophy in Cognitive Science Department, Middle East Technical University** by,

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Surname: Burcu Yargıçoğlu

Signature :

ABSTRACT

EFFECTS OF ATTACHMENT STYLES ON PREFRONTAL CORTEX DURING NATURALISTIC SOCIAL INTERACTION: AN FNIRS BASED HYPERSCANNING STUDY

Yargıçoğlu, Burcu
Ph.D., Department of Cognitive Science
Supervisor: Assist. Prof. Dr. Murat Perit Çakır

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This study investigates possible differences of prefrontal cortex (PFC) activity as well as brain-to-brain coordination across PFCs of dyads during naturalistic social interaction from an attachment theory perspective by employing functional near-infrared spectroscopy (fNIRS) hyperscanning. Male participants with right-hand dominance (N=48) were administered Turkish Experiences in Close Relationship Scale (Sumer, 2006) for assessment of predominant adult attachment styles (Secure:27, Insecure: 21) and played regular and reverse cooperative and competitive versions of the rock-paper-scissors (RPS) game to facilitate standardized social interaction. By using a novel method, significant inter-brain coherence were observed for both competition and cooperation tasks at fronto-polar cortex (FC) and dorsolateral PFC (DLPFC) bilaterally in a lateralized manner depending on the task type. Moreover, two-sample t-tests have revealed that attachment styles do have effects on FC oxygenated hemoglobin (HbO) activation. Overall, our findings suggest that FC, thought as a hub for metacognition, while contributing to social interaction, interestingly elicits activation differences w.r.t. attachment styles as well, with secure attachment orientation exhibiting stronger hemodynamic response, which may serve as a putative neuro-biologic marker underlying individual differences.

Keywords: Hyperscanning, fNIRS, Frontopolar cortex, PFC, Attachment theory

ÖZ

SOSYAL ETKİLEŞİMDE BAĞLANMA STİLLERİNİN PREFRONTAL KORTEKS ÜZERİNDEKİ ETKİLERİ: FNIRS HİPERTARAMA ÇALIŞMASI

Yargıçoğlu, Burcu

Doktora, Bilişsel Bilimler Bölümü

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Sosyal nörobilim alanında yapılan bu fonksiyonel yakın kızılötesi spektroskopisi (fNIRS) hipertarama çalışmasında, bağlanma kuramı da dikkate alınarak doğal sosyal etkileşim süresince prefrontal korteks (PFK) oksihemoglobin (HbO) aktivasyonundaki bireysel farklılıklar ve beyinler arası senkronizasyon incelenmiştir. 48 sağ-eli baskın yetişkin erkek katılımcının baskın bağlanma stilleri belirlenmiş ve çiftler halinde taş kağıt makas (TKM) oyununun yarışılan ve işbirliği yapılan ters ve düz versiyonlarını hem bireysel hem de yüz yüze durumda oynamaları istenmiştir. Özgün koherans farklılığı ölçüm metodu sayesinde yarışma ve işbirliği oyunlarında frontopolar kortekste (FK) ve TKM oyununun versiyonuna bağlı olarak bilateral dorsolateral PFK (DLPFK) üzerinde yanallaştırılmış beyinler arası anlamlı koherans gözlemlenmiştir. Buna ek olarak, 27 güvenli ve 21 güvenli olmayan bağlanma stiline sahip katılımcı gruplarının sosyal etkileşim esnasındaki FK HbO aktivasyonlarının birbirinden anlamlı olarak farklılaştığı gözlemlenmiştir. Deney sonuçları frontopolar korteksin sosyal etkileşimdeki rolünü göstermenin yanı sıra güvenli bağlanma stilinde bu bölgede daha güçlü bir aktivasyon gözlenmesi frontopolar bölgenin sosyal etkileşim sırasında bağlanma stillerine göre de aktivasyon farklılığı gösterebileceğine işaret etmektedir. Sonuç olarak, bu bulgunun bireysel farklılıkların açıklanmasına yardımcı olabilecek potansiyel bir nörobiyolojik gösterge olabileceği düşünülmektedir.

Anahtar Kelimeler: Bağlanma kuramı, fNIRS, Frontopolar korteks, Hipertarama, Prefrontal korteks

To my family and to all the kind people who have provided support

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LIST OF ABBREVIATIONS

AAP	Adult Attachment Projective Picture System
AAQ	Adult Attachment Questionnaire
AAS	Adult Attachment Style
ACC	Anterior Cingulate Cortex
AS	Attachment Style
AT	Attachment Theory
ATP	Anterior Temporal Pole
BA	Brodmann Area
BL	Baseline
BOLD	Blood Oxygen Level Dependent
BPD	Borderline Personality Disorder
CBF	Cerebral Blood Flow
Comp	Competition
Coop	Cooperation
CWT	Continuous Wavelet Transform
DMPFC	Dorsomedial Prefrontal Cortex
DLPFC	Dorsolateral Prefrontal Cortex
DWT	Discrete Wavelet Transform
ECR	Experiences in Close Relationship
EEG	Electroencephalography
FC	Frontopolar Cortex
FDR	False Discovery Rate

FIR	Finite Impulse Response
fMRI	Functional Magnetic Resonance Imaging
fNIRS	Functional Near Infrared Spectroscopy
HbO	Oxygenated Hemoglobin
HbR	Deoxygenated Hemoglobin
IBC	Inter-brain Coherence
IBS	Interpersonal Brain Synchronization
LED	Light-Emitting Diode
LPFC	Lateral Prefrontal Cortex
MEG	Magnetoencephalography
METU	Middle East Technical University
MPFC	Medial Prefrontal Cortex
Norm	Normal
OFC	Orbitofrontal Cortex
PCC	Posterior Cingulate Cortex
PFC	Prefrontal Cortex
Rev	Reverse
RoPFC	Rostral Prefrontal Cortex
RPS	Rock Paper Scissors
RQ	Relationship Questionnaire
RSQ	Relationship Styles Questionnaire
RST	Rest
SI	Stimulus Independent
SMA	Supplemental Motor Area
SO	Stimulus Oriented
STG	Superior Temporal Gyrus

STS	Superior Temporal Sulcus
TL	Turkish Lira
ToM	Theory of Mind
TPJ	Temporo-parietal Junction
VMPFC	Ventromedial Prefrontal Cortex
VTA	Ventral Tegmental Area
WTC	Wavelet Transform Coherence

CHAPTER 1

INTRODUCTION

The neuroscientific study of social interaction requires adopting an approach based on real social interaction and emotional engagement [2]. However, due to the limitations imposed by existing neuroimaging tools, the majority of social cognition studies are conducted by employing computerized tasks that simulate social encounters for individual subjects in isolation, without actual engagement with the environment and with other interlocutors. As a result, studies employing experimental procedures that enable real-world social encounters have become essential for advancing research in social neuroscience. This study aims to contribute to these efforts by investigating the neural correlates of human social interactions in a naturalistic context, similar to real-life situations. The goal of the study is to reveal prefrontal cortex (PFC) activity and brain-to-brain synchronization patterns across dyads who are engaged in various kinds of social tasks and identify possible differences with respect to attachment orientation. Specifically, two research questions are tried to be addressed; (1) what are the effects of naturalistic competitive and cooperative social interaction tasks on the degree of intra- and inter-brain activities observed at the prefrontal cortices of the participants, and (2) what are the differences with respect to predominant adult attachment styles.

Recent advancements in neuroscience have opened up the possibility for simultaneous neuroimaging of multiple brains, also called as hyperscanning, which allows the study of neural correlates of social interactions in an interactive manner. Hyperscanning with functional near-infrared spectroscopy (fNIRS) is a promising method for facilitating naturalistic social interactions during experiments due to its reliability and portability. Compared to current neuroimaging techniques, measurement with fNIRS devices imposes much less physical and psychological burden [3], reducing participants' discomfort. In addition, it enables robust data collection even in physical motion [4]. Thus, fNIRS hyperscanning opens the way for analyzing both intra-brain and inter-brain connectivity patterns of socially interacting individuals as they occur in real life. The importance of hyperscanning studies in social neuroscience research has been emphasized by several recent reviews [5] and studies [6, 7, 8].

Cooperation and competition are examples of different forms of social interaction that are utilized in our daily lives and thus in experimental setups which involve cognitive processing. Previous hyperscanning studies have shown that inter-brain coherence increases in certain PFC regions during cooperative social tasks. The studies [9, 10, 11] have demonstrated an increased brain-to-brain synchronization at the right prefrontal cortices of the interacting participants when they perform a computerized cooperation

task. Furthermore, the level of inter-brain coherence and cooperation success were found to be significantly correlated, whereas similar increases in coherence have not been observed during similar competitive tasks or individualized tasks. This finding suggested a possible link between cooperative behavior and neural synchrony in PFC [9, 10]. Moreover, few studies such as Baker et al. [10] and Pan et al. [11] have explored individual differences in association with computer-based cooperation tasks. Baker et al. [10] demonstrated sex-related differences such that female/female dyad's were observed to exhibit inter-brain coherence on their right temporal cortices, while male/male dyads in their right inferior prefrontal cortices. The same study reported no such significant coherence increase in male-female dyads. Pan et al. [11] investigated the cooperative behavior among lover, friend, and stranger dyads and showed that the nature of the relationship might affect the quality of social interaction. The study reported higher inter-brain coherence for lover pairs than friend and stranger pairs and identified inter-brain synchronization in their right superior frontal cortices.

Regarding individual differences in social behavior, attachment theory (AT) offers an important psychological framework to understand the dynamics of human relationships. AT was formulated by John Bowlby [12, 13, 14] and further extended by Mary Ainsworth [15]. According to AT, children have differences in their attachment patterns which is primarily shaped during the early experiences they had with their caregivers. These different patterns are organized into four categories, namely secure, avoidant, anxious and disorganized attachment styles [16]. Longitudinal studies show that the attachment patterns adopted through the relationship with the caregivers in childhood continue throughout life and affect all future social relationships in adulthood [17]. An extensive literature has grown up around the attachment theory [18], which is now being utilized as the major theory in studies of infant and toddler behavior and mental health, as well as in the assessment of adult relationship behaviors.

There have been many behavioral studies within the scope of attachment theory, demonstrating the influences of attachment styles on cognitive processing [19]. Studies reported observed differences with respect to the attachment style of the participants, which affects the performance of cognitive processes such as attention, decision making, affective processing and working memory that are needed when we socialize with our conspecifics. The dynamics of attachment system activation in adulthood were investigated in several studies which resulted in demonstration of the stress-attachment link, showing that the attachment system is activated during actual or symbolic stress-eliciting conditions [20, 21, 18]. Moreover, the studies documented anxious-ambivalent persons' heightened accessibility of attachment themes and worries in neutral conditions, signalling that the attachment system might always active for anxious-ambivalent. Moreover, combination of cognitive load beyond stress heightened accessibility to attachment worries in individuals with avoidant attachment orientation, showing avoidant persons might be using defensive suppression in non-load conditions [20]. These findings together with the role of PFC in social cognition (e.g. mentalization) provides an important motivation to investigate potential effects of adult attachment orientation in this study's context. The experimental setup provides a setting in which stranger dyads engage in naturalistic social interaction that impose a certain amount of cognitive load together with a motivation to win through monetary

prizes. The differences in inter-brain synchrony and activation levels with respect to attachment orientation may shed a light to future studies. The underlying neural mechanisms are yet to be understood and there is an increasing number of first-person and few second-person brain imaging studies (see Long et al. [22] for a detailed review of the current literature). This study aims to add further research data in the application of AT in social neuroscience by conducting a second-person study on individual differences in social cognition within the prefrontal cortex with respect to adult attachment styles. While doing so, compared to previous studies, the current study offers a naturalistic experimental procedure with control conditions that allow effective utilization of inter-brain coherence analysis for systematic assessment of the effects of different modes of socialization and attachment styles.

1.1 Research Questions

Within the scope of this work, there are four research questions, focusing on inter-brain (brain-to-brain) interactions between the participants' prefrontal cortex (PFC) activations during competitive and cooperative tasks as well as intra-brain activation differences between these two set of tasks.

The initial research question is related to the investigation of brain-to-brain interactions during social interactions, specifically concerning the inter-brain coherence during competitive and cooperative tasks. For this research goal, the RPS game with both competitive and cooperative tasks was conducted in pairs, and hyperscanning data were collected using two fNIRS devices. The second research question aims to identify differences in brain activations between different modes of social interactions. The third research question focuses on investigating the possible differences of brain-to-brain interactions from an attachment theory perspective during social interactions. Last but not least, the fourth research question is concerned with investigating possible differences of brain activations from the attachment theory perspective between different modes of social interaction (e.g., competition and cooperation).

Research questions and hypotheses based on previous findings are provided as follows:

Research Question 1: What are the effects of competitive and cooperative social interaction tasks on the prefrontal cortices of the interacting participants?

Research Question 1.1: Are there significant coherence increase differences at the prefrontal cortices of pairs during social tasks compared to solo tasks?

Research Question 1.2: Are there observable coherence increase differences at the prefrontal cortices for pairs who score better results at cooperation tasks compared to other pairs?

Hypothesis 1: The coherence in participants' right superior frontal cortices will be increased significantly during cooperation.

Research Question 2: What are the differences in brain activation levels during competitive and cooperative social interaction tasks at the prefrontal cortex?

Hypothesis 2: Competition phases will lead to higher levels of activity in the medial prefrontal cortex (MPFC).

Research Question 3: What are the effects of attachment styles on the degree of inter-brain synchrony in prefrontal cortex during competitive and cooperative social interaction tasks?

Research Question 3.1: Are there observable coherence increase differences at the prefrontal cortices for pairs with the same attachment styles compared to pairs with different attachment styles?

Hypothesis 3: Inter-brain coherence will be higher in dyads having participants with the same attachment style.

Research Question 4: What are the effects of attachment styles on the degree of prefrontal cortex activity during competitive and cooperative social interaction tasks?

Hypothesis 4.1: Frontopolar region will be activated more during socially rewarding cooperation trials.

Hypothesis 4.2: Frontopolar region will elicit more activation in secure participants compared to insecure participants.

1.2 Organization of the Thesis

The thesis is structured as follows. The 'Literature Review' section summarizes the findings of related studies and provides a conceptual background for the thesis. The 'Materials and Methods' section provides the details regarding the experiment that has been carried out as well as data acquisition and analysis details. 'Results' section provides the main results obtained from this study. 'Discussion, Conclusion and Future Directions' section concludes the thesis with the main findings concerned with the research questions and provides discussion in relation to prior related studies, as well as pointers for future studies. Finally, supplementary contents, including the M.E.T.U. human subjects research approval, Edinburgh handedness questionnaire, Experiences in Close Relationship scale used in the experiment, significant inter-brain coherence increase results, and a cirruculum vitae are provided in the Appendix.

CHAPTER 2

LITERATURE REVIEW

2.1 Functional Near-Infrared Spectroscopy Hyperscanning

2.1.1 Functional Near-Infrared Spectroscopy

Functional near-infrared spectroscopy (fNIRS) has acquired widespread acceptance among cognitive neuroscientists, which is indicated by the steady increase in the number of research studies that employed fNIRS to monitor brain activation in the past 20 years [23]. FNIRS technology provides an easy and non-invasive way of measuring changes in concentrations of oxygenated and deoxygenated hemoglobin (HbO and HbR) in biological tissue. To infer brain activity, fNIRS, like fMRI, uses the principle of neurovascular coupling, namely the strong link between neural activity and cerebral blood flow [4]. Cognitive neuroscientists are increasingly using the approach as a neuroimaging tool to examine a variety of cognitive phenomena, including social cognition.

Despite having a number of drawbacks, such as having lower temporal resolution compared to EEG and MEG, lower spatial resolution compared to fMRI, and limited penetration depth into cerebral cortex, fNIRS has a number of advantages over other neuroimaging techniques. The way fNIRS light sources and probes are positioned over the scalp and the optical properties of light propagation in cerebral tissue brings spatial resolution in the order of centimeter cube, which is better than the spatial resolution of EEG. As compared to high spatial resolution imaging modalities such as fMRI and PET, fNIRS offers improved temporal resolution due to the reduced cost of spectroscopic computations involved with estimating oxy- and deoxy-hemoglobin concentrations. The fixed positions of the optodes over the scalp also make fNIRS less susceptible to motion artifacts as compared to fMRI where head motion causes shifts over all voxel locations.

Most importantly, as noted by Hari & Kujala, "...the current challenge for brain imaging is to bring every day human interaction, occurring in a complex natural environment between two or more subjects, into the laboratory" [24, p. 454]. fNIRS is a promising technique for monitoring cerebral oxygenation changes during naturally occurring social interaction since it imposes far less physical and psychological burden during data acquisition [3]. fNIRS decreases participant discomfort, permits data collection for longer durations of time, and allows measurement of activation during tasks that

involve mobility, compared to other brain imaging modalities [4]. Thus, fNIRS offers important advantages for monitoring the brain in more naturalistic experimental environments, especially in contrast to fMRI and MEG techniques.

2.1.2 Hyperscanning

FNIRS opens up the possibility to employ different experimental paradigms such as hyperscanning, in which cerebral activity is acquired simultaneously from at least two people while they are engaged in various forms of joint interactions. In addition to analyzing each subject's brain responses in the context of a social task, hyperscanning also makes it possible to explore the degree of mutual relationship across two or more participants' brain regions during the course of social interaction [5]. The importance and potential of hyperscanning studies in social neuroscience studies are further elaborated in [6], [7], and [8]. Babiloni & Astolfi [5] provides a literature review on studies that utilize hyperscanning.

The following subsection summarizes various existing fNIRS based hyperscanning studies and their findings during social interaction.

2.1.3 Inter-Brain Synchronization

One of the first findings in fNIRS hyperscanning is the discovery of the inter-brain synchronization / coherence (IBS / IBC) in the right superior frontal cortices of participant pairs who engage in cooperative behaviour. Cui et. al. [9] have performed an fNIRS hyperscanning study utilizing cooperative and competitive variations of a computer-based key press task. Pairs were instructed to press a certain key after a go signal appeared on their screen. In the cooperation task, the goal was to keypress as close to their partner as possible in terms of timing, whereas in the competition task, the goal was to press the key as fast as possible and beat their partner. Inter-brain coherence was observed in the cooperative task, but not in the competitive task. In addition, coherence increase was observed to be positively associated with the performance of the cooperation.

Later on, Baker et al. [10] have performed an fNIRS hyperscanning study to investigate whether the sex composition of dyads influences behavioral and neural responses during social interaction. Regarding inter-brain synchrony, Baker et al. reported sex-related differences such that pairs with female subjects had inter-brain coherence in the right temporal cortex, whereas pairs with male subjects had in the right inferior prefrontal cortex. Pairs with a female and a male subject lacked significant coherence. In addition, inter-brain coherence was found to be positively correlated with cooperation performance, but only for same-sex pairs. Finally, inter-brain coherence in the frontopolar cortex (BA10) was also observed only for the male-male pairs during the cooperation task.

Pan et al. [11] employed fNIRS-based hyperscanning to investigate interpersonal brain synchronization among lover, friend, and stranger pairs during a button press task similar to the one used by Cui et al. [9]. Pan et al. discovered that lover dyads cooperated better than friend and stranger pairs, and they identified inter-brain synchronization in the lovers' right superior frontal cortices, which concurs with prior findings. The IBS that was found in lover dyads was also correlated with their cooperative performance. Friends and strangers, on the other hand, showed no significant inter-brain synchronization.

In a group-based fNIRS hyperscanning study [25], cooperative verbal communication was conducted in groups of four young adults. An enhancement in interpersonal neural synchronization of Frontopolar Cortex was observed during unstructured communication as opposed to silent thinking. The results of this study suggest that natural and cooperative verbal conversation between people can lead to increased inter-brain synchronization in the frontopolar area.

Reindl et al. [26] conducted another fNIRS based hyperscanning study in which 5–9-year-old children played a cooperative and competitive game with their caregivers, usually with their mothers, and an adult stranger. The study reported synchronized brain activities for the dorsolateral prefrontal and the frontopolar cortices of parents and children during cooperation, which was diminished during the competitive control condition and when the child played with an adult stranger. Furthermore, Reindl et al. also investigated the links between inter-brain synchrony during cooperation and emotion regulation of children and their parents, and observed that stronger inter-brain synchrony in the frontopolar cortex was related to better emotion regulation of both the parent and the child. As a result, they have come to the conclusion that inter-brain synchrony could be an underlying neural mechanism of the emotional bond between the parent and the child, which is linked to the development of adaptive emotion regulation in children.

Miller et al. [27] have examined parent-child brain-to-brain synchrony with fNIRS, specifically analyzing right prefrontal cortex and temporoparietal cortex hemodynamic activity. During the cooperation condition, they observed higher inter-brain synchronization in the right dorsolateral PFC and frontopolar cortex. Overall they observed that mother-child dyads have higher inter-brain synchrony during cooperation. Moreover, Miller et al. also found differences among mother-son and mother-daughter dyads. The inter-brain synchrony in mother-son dyads was lower during the independent task and showed a higher increase in response to cooperation compared to mother-daughter dyads. Finally, the researchers looked into the potential correlation between inter-brain synchrony and child attachment. Experiences in Close Relationships-Revised Child Questionnaire [28] was used as a measure of child attachment. Their findings did not reveal any strong evidence for such a link. However, preliminary evidence suggests a link between avoidant attachment style in children and poor behavioral performance with less synchrony in the right frontopolar cortex.

In a recent fNIRS hyperscanning study by Nguyen et al. [29], inter-brain coherence among mother-child dyads (child participants were 5 years old) was investigated during a cooperative versus independent problem-solving activity featuring a tangram puzzle

game. Mother-child pairs had to either cooperate or work individually. The findings were consistent with prior studies, which showed a significant increase in inter-brain coherence during cooperation compared to both independent and control conditions, along with a positive correlation with task performance. In addition to these findings, behavioral reciprocity has been assessed utilizing Coding System for Mother-Child Interactions (CSMCI). Increased inter-brain coherence during cooperation has been linked to higher behavioral reciprocity, suggesting that neural synchrony could be used as a biomarker for parent-child interaction quality.

2.2 Attachment Theory

2.2.1 Introduction

Attachment Theory is one of the most widely utilized developmental psychology frameworks in the study of social and affective behavior. According to this theory, attachment is the result of innate, interrelated human predispositions for infants to seek the attention of adults that is necessary for infant's survival, and humans, especially infants, rely on attachment figures for protection, comfort, and emotional regulation [12, 13, 14]. It has been theorized that we have an "attachment behavioral system", which is activated mostly under threatening circumstances, and there are observed systematic differences in the attachment orientation of individuals that can be broadly classified as; secure and insecure. Insecure attachment orientation can also be divided into anxious, avoidant, and disorganized [16, 30]. Disturbance of the initial attachment bond between the child and the primary caregiver renders a person insecure as an adult, which continues throughout the life span [31].

Since its inception, an extensive body of literature has emerged around the concept of attachment theory, and significant progress has been made by behavioral experiments, demonstrating the impact of individual attachment style differences on emotion processing and social cognition. These differences are observed to affect performance in tasks related to cognitive processes such as attention, decision-making, and working memory [19]. Although the brain mechanisms governing emotional experience and mood have been the subject of decades of extensive investigation in both cognitive neuroscience and clinical psychiatry, there has been a knowledge gap regarding the neural underpinnings of these individual differences. In particular, there is a major gap between the psychological models that attachment theory brings and the neuroscientific models outlined by emotion research [22]. The reason for this gap can be partly due to the fact that neural underpinnings of human emotion are still yet to be understood, and there are only a few neuroscience studies focusing on adult attachment style (AAS) induced individual differences. Therefore, utilizing attachment theory as a framework may provide fruitful insights regarding the individual differences observed at neural and psychological levels in emotion studies.

Areas within the brain that are associated with emotion are often located in subcortical regions and are typically considered evolutionarily conserved. Examples of these

areas are the hypothalamus, ventral striatum, and amygdala. Brain regions that were not initially considered as part of the limbic system are now known to be involved in emotion, such as regions in the prefrontal cortex (PFC). One major motivation of this thesis is to investigate the effects of attachment style differences on cognitive processing within PFC through imaging techniques in naturalistic and interactive social contexts. In order to create a more ecologically valid social setting, fNIRS imaging technology with hyperscanning methodology was adopted to measure the PFC activity of interlocutors during social interaction. More specifically, this study investigates the possible effects of AAS differences on the activation of related brain regions (PFC regions that can be monitored by fNIRS) during cooperative and competitive social interactions. The following subsections provide background knowledge on Attachment Theory and describe how it continues throughout adulthood. Furthermore, existing attachment style classification methodologies are provided, along with a summary of the observed behavioral differences with respect to these attachment styles.

2.2.2 Fundamentals of Attachment Theory

Over 60 years ago, John Bowlby formulated the attachment theory [12, 13, 14], which is further extended by Mary Ainsworth [15] to establish a psychological framework to further our understanding of the dynamics of human relationships. Bowlby argued that children's early ties with their caregivers have a profound life-long impact on their lives. According to Bowlby, attachment keeps the infant close to the mother, increasing the child's chances of survival. Bowlby and Ainsworth assert that attachment's role is to meet a child's desire for safety and protection and form a secure base that is crucial in childhood. Furthermore, they claim that early experiences with the caregivers during childhood shape the future social relationships people form later in their lives, and that childhood plays an important role in attachment. Since then, a large body of literature has developed around the concept of attachment theory [18], and it is now being utilized as the major theory in studies of infant and toddler behavior and mental health, as well as in the assessment of adult relationship behaviors.

To begin with, the word attachment can have several meanings. According to Ainsworth, attachment is "...an affectional tie that one person or animal forms between himself and another specific one – a tie that binds them together in space and endures over time." [32, p. 50]. Attachment is more than two people connecting with each other. It's a bond that entails a desire for regular contact with that person as well as experience of distress in times of separation. Attachment behavior, on the other hand, is defined as any form of behavior that results in the proximity of a preferred individual, the caregiver during childhood.

Mary Ainsworth introduced the Strange Situation Protocol, which is a test situation used to observe attachment behavior of 1-year-old children under conditions of novelty and alarm. Infants' responses to novel objects and situations are explored as well as their responses to separation from and eventual reunion with the mother. The behavioral findings have shown that the presence of the mother increases the exploratory behavior of children to the strange or novel situation, whereas the absence

of the mother decreases this behavior and leads to an increase in the attachment behavior. While the mother is absent, the child expresses behaviors such as searching or crying to promote proximity and when the mother returns attachment behavior does not immediately subside and exploratory behavior remains lower than the pre-separation episodes. Along with these observed general attachment behavior in children, distinct attachment patterns were also observed based on the experiences they had with their early caregivers. Ainsworth [33] proposed the term attachment style to classify infants' different patterns of behavioral responses to separations and reunions with their mothers as described in the episodes of the Strange Situation Protocol. The infants have been classified into styles as "secure," "avoidant," or "anxious." Later on, a fourth style called "disorganized" is introduced by Main and Solomon [30].

Secure infants appear to use their mother's presence as a secure base, which he or she can explore the world with confidence. When the mother leaves, the kid loses interest in exploring the environment and shows discomfort, but soon recover and continue to explore the world. When the mother returns, the child greets her with enthusiasm and seeks proximity and engagement with her, begins exploring the environment, and can play independently once again. Secure infants seem to acquire working models of successful attainment to security. Mothers of these infants are emotionally present in times of need and receptive to their child's proximity-seeking behavior, according to home observations [16].

Avoidant infants appear to be distant from the mother. When the mother leaves the room, the child shows little discomfort and seems like he or she is unaware of their mother's departure, and when she returns, the child avoids her. Therefore, avoidant infants seem to acquire working models with a deactivated attachment system. Their moms, according to home observations, are emotionally rigid, as well as hostile and dismissive of their infants' proximity-seeking efforts [16].

Anxious infants (also called as anxious-ambivalent or anxious-resistant) appear to be extremely distressed when they are separated from their mothers. They emotionally protest the departure, often with anger, and get irritable and resistant. When the mother returns, the child exhibit ambivalent responses to their mothers such that he/she approaches her for attention but furiously refuses to be picked up by her, being unable to be soothed and comforted. Anxious infants seem to acquire hyper-activated attachment system working models. During home visits, nervous infants and their mothers' relationships were marked by a lack of harmony and caregivers' constant attention [16].

Disorganized infants appear to have a breakdown in the organization of their attachment patterns. They either seem to switch back and forth between different attachment patterns or exhibit odd behavior. The child may be fluctuating between hyperactivating or deactivating strategies or acting unusual such as lying face-down on the floor without moving during reunion with their mothers after a separation or sitting under a table, demonstrating no apparent proximity-seeking behavior [30].

2.2.3 Attachment in Adults

While the attachment system is very important in early childhood for survival, the system is thought to continue its activation throughout our lives. According to Bowlby [31], the attachment system is activated with a threat, creating a risk for the survival of the being, which increases the desire for other people's protection. In the absence of a threat, help from others is not needed; therefore, dedicating time for other activities needed for a living can be pursued instead of seeking proximity for protection.

Bowlby [31] claims that the attachment system still activates the need for proximity seeking in threat conditions but this strategy is enriched in adulthood. During stressful times or when a threat is perceived, proximity-seeking to the attachment figures can be achieved mentally in addition to physical presence [34]. While occurring with a lower threshold in childhood, these processes continue during adulthood with higher thresholds since most adults develop mechanisms for resiliency. Adults are able to self-soothe and regulate their emotions by imagining their secure interactions through activating mental representations of their significant others who elicit care. The mental representations of attachment figures become symbolic sources of protection, creating feelings of safety and security.

Bowlby argues that the behavioral system in adults has acquired learned mechanisms that reflect a history of activation in various contexts [31]. Experiences with the environment shape cognitive-behavioral mechanisms, adjusting to certain patterns, depending on the effectiveness of the strategies used. An individual's behavioral system happens to be adjusted based on the continuous relationship experience with their family members or partners [35]. The majority of research on individual differences in adult attachment has concentrated on the patterns of emotions, expectations, needs, and behavior acquired as a result of early attachment experiences, often with the parents. The attachment style represents an individual's accessible working models as well as the attachment strategies he or she uses pre-dominantly within the relationships.

2.2.4 Attachment Style Classification

Attachment style classification has begun with Hazan and Shaver's [36, 37] introduction of short prototypical descriptions for secure, anxious, and avoidant patterns of attachment. From these descriptions, Simpson [38] created a 13-item questionnaire and called it the Adult Attachment Questionnaire (AAQ), which represented the attachment styles in two dimensions for the first time. Independent of Simpson's work, Collins and Read [39], created an 18-item Adult Attachment Scale (AAS). Later on, the Attachment Style Questionnaire (ASQ) was created by Feeney et al. [40] and followed by the development of the Relationship Styles Questionnaire (RSQ), a 30-item inventory, by Griffin and Bartholomew [41], who also considered Hazan and Shaver's [36] short descriptive prototypes.

As summarized above, there are a number of different methods and questionnaires to categorize adult attachment styles and one of these methods is needed to be selected for our experimental setup. Given the experiments are held with Turkish participants, the importance of a Turkish questionnaire arises. Sümer & Güngör [42] translated the RQ and the RSQ questionnaires to Turkish and examined its reliability and validity of these two commonly used measures of attachment styles on the Turkish sample and made a cross-cultural comparison with a U.S. sample, with good outcomes. Later Sümer [43], translated and reviewed Experiences in Close Relationship Scale (ECR) using Turkish students and concluded that: "the discriminant function analyses on the attachment groups showed that the attachment groups formed on the basis of the ECR dimensions were more congruent with the Four-Category Model than the attachment groups formed using the subscales of the RQ and the RSQ" [43, p. 1].

Given that we would like to use a commonly accepted two-scale outcome questionnaire, plus the Turkish translated version which had already been validated in a scientific study, Sümer's ECR [43] seems to be the logical choice for our experimental setup. The Turkish version of the Experiences in Close Relationship scale (ECR), the so-called YİYE questionnaire, was prepared in an Excel sheet, which was used to classify the participants into 2-dimensional Avoidant and Anxious characteristics levels. The questionnaire is illustrated in Figure 24 in Appendix section.

2.2.5 Attachment Style Effects

Behavioral findings have demonstrated that distinct adult attachment styles are associated with differences in various cognitive and affective processing [18, 20, 21, 44, 45]. A review of the findings are provided in Vrticka & Vuilleumier [19], suggesting that individuals having distinct attachment styles possess performance differences in attention, decision making, working memory and affective processing. The underlying neural mechanisms for these differences are still under discussion, which forms the main motivation of this thesis study, especially in brain regions where emotion and cognition mechanisms interact with each other.

There has been an increasing number of social neuroscience studies to identify underlying neural correlates of human attachment behaviour. Most of the studies explore the potential differences in the brain with respect to different attachment patterns in order to understand the roots for secure, anxious, and avoidant attachment behavior. While this is being done, varying stimuli have been studied with different brain imaging modalities and with different attachment assessment measures. Extensive work has begun to emerge around the neuroscience of attachment behavior to develop an understanding of the neural mechanisms that influence human social behavior. In this subsection, comprehensive studies, as well as studies that relate with the prefrontal cortex, are summarized to compare and interpret the results obtained within the scope of this thesis.

Fonagy and Luyten [46] provides a neurodevelopmental perspective on the neurobiology of attachment and mentalizing. According to them, the attachment system has a major role in stress modulation and survival in situations of perceived threat. Activation of the attachment system leads to proximity-seeking with the attachment figure that can be achieved physically and mentally through representations of attachment experiences. This results in down-regulating the stress and an increase in exploration of the world. Secure individuals internalize this pattern and gradually generalize to different circumstances. The attachment system is closely related with reward and mentalization systems which serves to rewarding experience of attachment relationships and the necessary understanding of self and others to navigate in complex social situations. Relationships become progressively gratifying for secure individuals, and experiences of effective distress down-regulation contribute to autonomy and confidence in one's ability to deal with adversity. Whereas insecure individuals have a reduced reward in their attachment experiences and may involve anxiety, anger, and frustration as well if the individual has an adverse early attachment history. In addition, they argue that the cumulative nature of the interactions that take place with the individual's attachment relationships, particularly early attachments during infancy, shapes the nature of an individual's mentalizing capacity. Early positive experiences with the caregiver improve the child's ability to acquire mentalizing capacities and consequently promotes mentalizing growth through interaction with the conspecifics. Whereas negative experiences lead to mentalizing capacity impairments. Mentalization involves automatic and controlled mentalizing, in which automatic mentalizing is described as fast implicit processing of information associated with evolutionary older brain circuits and facilitating fight/flight responses and survival. It involves basal ganglia, amygdala, VMPFC, dorsal ACC, and lateral temporal cortex. Whereas, controlled mentalizing is evolutionary new and is needed in complex social situations allowing slow, explicit, verbal, reflective and conscious processing of social information. It involves MPFC, LPFC, rostral ACC, lateral and medial parietal cortices and medial temporal lobe. In times of stress, controlled mentalization is switched to automatic mentalization in which the attachment history of a person affects three-fold; the threshold for the switch, the amount and the duration of loss for controlled mentalization [46]. During perceived stress, secure individuals seem to be able to pursue controlled mentalizing longer, more effectively and recover faster compared to insecure individuals. On the other hand, the individuals that use attachment hyperactivating strategies, such as people having anxious-ambivalent attachment patterns, have a low threshold for switching to non-mentalizing modes, longer durations without controlled mentalizing, and later recovery compared to secure individuals. Lastly, individuals that internalized attachment deactivating strategies, such as people having avoidant attachment patterns, seems to have a higher threshold and be able to continue controlled mentalizing under very stressful conditions up to a certain degree where their strategy fail and feel insecure together with high emotional reactions [47].

In a recent study, Long et al. [22] reviews first-person and second-person attachment related social neuroscience studies, and suggests that prototypical attachment pathways linked to attachment patterns and proposes an associated functional neuro-anatomical model of human attachment based on the available evidence. They think that the attachment system's activations in early childhood follow a prototypical initial pathway,

and over the years, the repeated outcomes of this pathway, shaped through the early caregiving environment, become reflected in attachment-derived internal working models leading to individual differences. Different prototypical attachment pathways are formed as derivatives specific to secure, avoidant, and anxious attachment. Furthermore, considering the previous neuroimaging studies and the processes within the attachment pathways, they propose a functional neuro-anatomic model of human attachment advancing their prior work [19, 48]. On a neurological level, they argue that the human attachment system is comprised of an affective evaluation (emotional mentalization) and a cognitive control (cognitive mentalization) network. The affective evaluation network contains aversion (ACC, insula, hippocampus, amygdala, ATP) and approach (vmPFC, OFC, ventral striatum, hypothalamus, VTA) modules that are two independent neurobiological systems in a dynamic push-pull balance, encoding positive and negative social emotional states respectively in an automatic, rapid, and unconscious fashion. They also propose that dopamine, oxytocin (and vasopressin), endogenous opioids, cortisol, serotonin, androgens/estrogen, etc. further mediate the activity within the affective evaluation network. On the other hand, the cognitive control network involves emotion regulation (LOFC, DLPFC) and mental state representation (MPFC, PCC, pSTS/TPJ, aSTG, fusiform gyrus) modules that are voluntary and conscious, the latter being involved in processes related to mentalizing, theory of mind (ToM).

Kim et al. [49] showed that secure mothers tend to employ more efficient cognitive mentalization when interacting with children. It has been observed that secure mothers possess larger grey matter volume and higher activation in response to hearing baby cries in STS, fusiform gyrus and certain areas of PFC including BA10, BA47, superior frontal and orbital gyrus. Insecure mothers, on the other hand, had higher hippocampal reactions as a response.

Coan et al. [6] had an experiment with female participants while holding their husband's hand and being threatened with electrical shocks. They discovered a reverse correlation with the reported marital quality and activity in PFC cortical areas as well as the anterior insula and hypothalamus. The higher the quality, the lower the activation observed during shock anticipation.

Whereas, Buchheim et al. [50] found association between traumatic image content and disorganized attachment. When traumatic image content increased, only people with disorganized attachment showed greater activation in the lateral PFC areas, as well as the amygdala and hippocampus.

Strathearn et al. [51] performed an fMRI study to investigate brain reward and peripheral oxytocin responses of mothers while viewing their infant's smiling and crying faces. Adult Attachment Interview was utilized to classify mothers' attachment patterns. The study demonstrated that secure mothers have increased activation of mesocorticolimbic reward brain regions (ventral striatum, medial PFC) compared to avoidant mothers when they view their infant's smiling face. In addition, secure mothers had an increased peripheral oxytocin response while interacting with their infants. Whereas, in response to infant's sad faces, while secure mothers showed

greater activation in reward processing regions, avoidant mothers showed greater activation of DLPFC and anterior insula.

Warren et al. [52] employed an emotion-word Stroop task, in which participants were asked to determine the color of words that were either unpleasant, pleasant or neutral, disregarding their meaning. The findings demonstrated that an insecure attachment style was linked to poor task performance and increased activity in both the dorsolateral PFC and the OFC at the same time.

Baskak et al. [53] have performed an fNIRS study to assess the elationship between attachment styles and ToM. For this purpose, Reading the Mind from the Eyes Test (RMET) has been employed together with the RSQ attachment style questionnaire. Subjects were shown eye photographs and asked to guess the mental state (ToM condition), and for the control condition subjects were asked to guess the sex of the individual in the same photographs shown in ToM condition. As a result, they have observed ToM related activity in the right hemisphere, particularly including the right inferior frontal, bilateral middle frontal, inferior and superior temporal, and the adjacent parietal cortices. The researchers have observed cortical activity differences with respect to attachment styles which suggests potential effects on the representation of ToM. During task condition, the secure attachment style was associated with higher activity in the right posterior superior temporal cortex and adjacent inferior parietal cortex. In contrary, avoidant attachment score were found to be negatively correlated with the right superior temporal cortex activity.

Nolte et al. [54] has looked at how stress affected mentalization in an fMRI study by utilizing a modified version of RMET. Adult participants were administered personalized general and attachment-related stress induction procedures (GSI and ASI). The results have revealed reduced activation in the left posterior superior temporal sulcus (STS), left inferior frontal gyrus, and left temporoparietal junction (TPJ) after attachment-related stress (ASI) exposure. Furthermore, after the ASI, the left middle frontal gyrus and left anterior insula showed increased functional connectivity to the left posterior STS. This study suggests that stress that is related to attachment has effects on brain regions related to mentalization.

Buccheim et al. [55] have performed an fMRI study to investigate attachment system activations between Borderline Personality Disorder (BPD) patients and control subjects since BPD has been linked with insecure attachment pattern, especially with the disorganized/unresolved pattern. Both groups were shown pictures from Adult Attachment Projective Picture System (AAP) to activate their attachment system and have been identified as having resolved or unresolved attachment patterns through narrative assessment. All BPD patients were classified with the unresolved attachment pattern. The results have shown increased amygdala activation for unresolved control and unresolved BPD patients compared to resolved participants. All resolved and unresolved control subjects have shown higher activation in rostral cingulate zone and finally only the unresolved control subjects have shown higher activation of the right DLPFC.

Canterberry and Gillath [56] have investigated the effects of attachment security priming and whether it has differences based on the attachment styles assessed by ECR in an fMRI study. Explicit and implicit secure and insecure priming have been employed together with an affective priming task in which subjects rated their likes for the target images. Explicit security priming, in contrast to neutral tasks, has led to right MFC (BA6) activation, and in contrast to insecurity priming, it has led to higher activation in right postcentral gyrus, left middle frontal gyrus (BA 10), left fusiform (BA 37), and parahippocampal gyrus (BA 19). It also activated the bilateral cerebellum and right middle temporal gyrus (BA 37). When the insecurity and neutral contrast was examined, the left superior and middle temporal gyri (BA 22) as well as the OFC (BA 47) showed increased activation. The superior temporal gyrus (BA 22) was activated for the explicit insecurity and security contrast. They had also demonstrated activation increase for implicit priming and activation differences with respect to the attachment anxiety and avoidance in several brain areas in their study.

Choi et al. [57] have investigated activation differences with respect to the attachment security in children at the age of 9. The study has utilized fMRI monitoring, Separation Anxiety Test (SAT) for attachment style assessment, and AAP picture set. The results have revealed differences in neural activity for frontal, limbic and basal ganglia areas and demonstrated higher neuronal activity in securely attached children for dorsolateral prefrontal cortex, amygdala, cingulate cortex and striatum.

Gillath et al. [58] encouraged participants to think or stop thinking about bad relationship scenarios. When thinking about bad scenarios, anxious subjects showed higher activity in the ATP, hippocampus, and dorsal ACC, whereas they showed less activity in the OFC during the stop thinking phases. High attachment avoidance, on the other hand, were linked to prolonged activity in the subcallosal cingulate and medial frontal gyrus (BA9) during either phases. An extended similar study has been conducted by Vrticka et al. [44] in which subjects visualized positive or negative social and non-social scenes. While doing so, they were asked to either attend to scenes, mentally reappraise, or suppress their emotional responses. Attachment avoidance was linked with the recruitment of DLPFC, mOFC and ACC. During reappraisal of negative social stimuli, they showed sustained increases in DLPFC and left amygdala activity. When suppressing positive social stimuli they showed increased activation in the supplementary motor region and ventral caudate. On the other hand, anxious attachment was found to be associated with higher activation of the left parahippocampal cortex to positive stimuli, and higher activation of right amygdala to negative stimuli. According to Vrticka & Vuilleumier [19], these brain imaging data support that avoidantly attached individuals utilize emotion suppression in social situations.

2.3 Prefrontal Cortex

The prefrontal cortex (PFC) has been demonstrated to have a crucial role in higher-order cognitive functioning and emotion processing, both of which contribute to social behaviour. Higher-order cognitive functions are also called executive functions and include functions such as planning, reasoning, problem-solving, attentional control, monitoring, and the ability to orchestrate thoughts and actions according to internal goals [59].

According to Stuss [60], there are four main categories of frontal functions, namely energization ("the process of initiation or sustaining responses"), task setting/planning ("the ability to establish a stimulus-response relationship to respond to a target with specific attributes"), monitoring/checking ("the process of checking a task over time and for quality control"), and metacognition ("orchestrating the energization, motivation, emotional perspective, and executive capacities that are necessary to accomplish complex, novel tasks"). Moreover, the detriment of certain PFC areas such as the VMPFC revealed a wide range of emotional and behavioral disturbances, including difficulties in integrating the motivational, emotional, social, rewarding, and risky aspects of behaviors that contribute to the regulation of social behaviour.

Over the last few years, structural neuroimaging and animal studies have revealed that the PFC has a plethora of connections both within and outside of the PFC, including subcortical, limbic, cerebellar, and cortical areas [61]. The prefrontal cortex can be divided into areas considering functional connectivity and specialization. There are proposals regarding asymmetrical functionalization in the prefrontal cortex (PFC). According to Burgess & Stuss [61] and Stuss [60], executive functions are found to be associated with different regions within PFC; DMPFC for energization, left DLPFC for task setting, right DLPFC for monitoring, and frontopolar cortex for metacognition.

In the following subsections, PFC regions that can be monitored by fNIRS devices used in the current study are introduced, namely the lateral prefrontal cortex and the frontopolar cortex. Evidence from previous studies regarding each regions' possible underlying cognitive role is briefly summarized in order to facilitate the findings obtained within the scope of this thesis work.

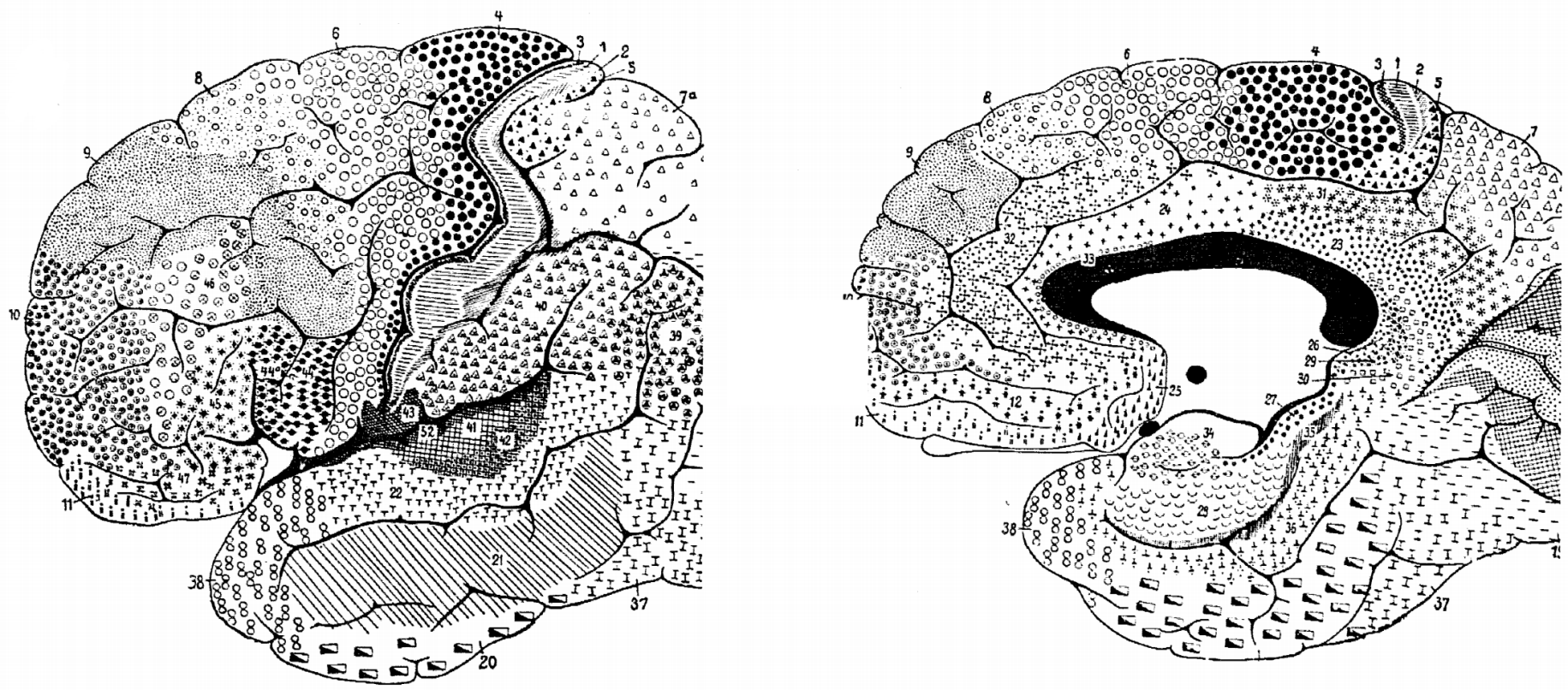


Figure 1: Brodmann Areas of human prefrontal cortex. Image is from Petrides & Pandya, 1999, p. 1012 [1]

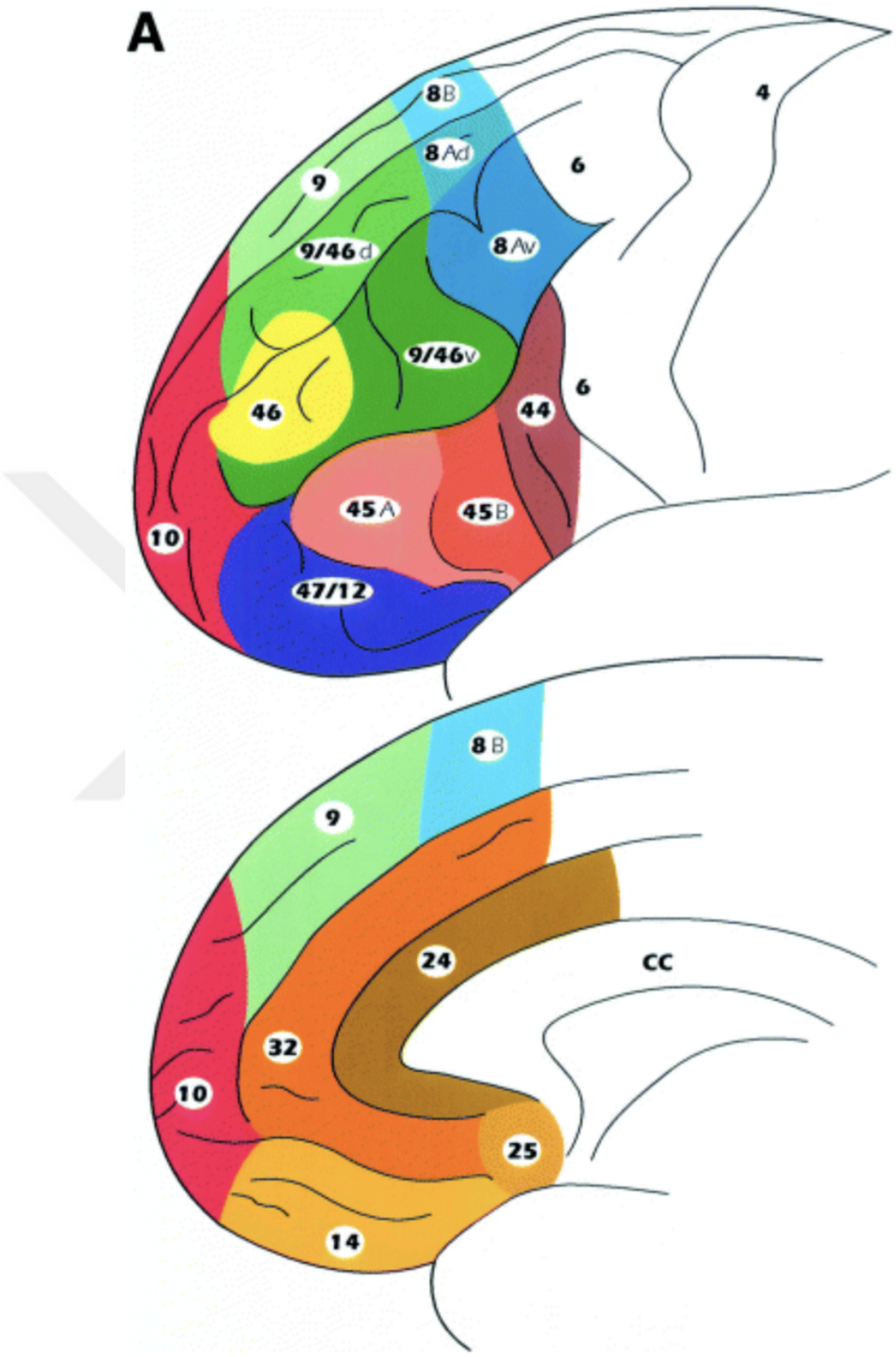


Figure 2: Brodmann Areas of human prefrontal cortex. Image is from Petrides & Pandya, 1999, p. 1015 [1]

2.3.1 Lateral Prefrontal Cortex

The differences in cytoarchitecture and connectivity with other parts of the brain, suggest that areas within PFC might have differing roles for the higher-order cognitive functioning. With the aim of revealing the functional organization within PFC, lesion studies in human patients as well as macaque monkeys have been performed [62] together with a substantial amount of imaging studies that attempt to understand the functional roles of these regions. The lesion studies and comparative analysis suggest two organizations within the lateral PFC [62]. The first one is the rostral-caudal organization and second one is the dorsal-ventral organization in the mid-lateral part of PFC.

One major difference based on anatomical studies are observed among the dorsolateral prefrontal cortex (DLPFC) including Brodmann areas 9, 46, 9/46, and the ventrolateral prefrontal cortex (VLPFC) including Brodmann areas 44, 45, 47/12 [63]. The DLPFC (BA 9, 46, 9/46) has been associated with a variety of cognitive functions, such as retention of spatial information, selection of responses, monitoring and manipulation within the working memory. DLPFC is also linked with functions that facilitate memory, achieve organization prior to encoding, and validate and assess the long-term memory representations [64].

The mid-dorsolateral PFC (BA 9, 46, 9/46) is connected with the hippocampal / parahippocampal area through the retrosplenial cortex [1], and hence through this link, it is thought to achieve its control on the working memory [62]. Lesions limited with the middle part of the dorsolateral frontal cortex yielded deficits on working memory tasks that needed the capacity to track previous stimuli selections. In one experiment [65], the monkeys with damage on mid-dorsolateral frontal cortex were observed to lack the ability to recall their previous selection from a set of stimuli, even though they had no problem in recognizing that they had already seen the stimuli. On the other hand, monkeys with damage in their posterior dorsolateral frontal cortex were observed to be intact in their ability to recognize the stimuli and remember their previous selections. These findings have demonstrated that deterioration of working memory functions for the monkeys having lesions on mid-dorsolateral frontal cortex resulted from the necessity of monitoring, delineating the mid-dorsolateral frontal cortex having a role in mediating the monitoring of self-generated responses [65].

The mid-ventrolateral prefrontal cortex (BA 47/12) has been observed to engage in active selection, judgment and comparison of data contained in short and long-term memory. In one study, the right mid-ventrolateral PFC was found to be involved in active explicit decision-making about the relative familiarity of stimuli [66]. The left mid-ventrolateral PFC is also found to be employed during verbal episodic and semantic retrieval [62].

Ventrolateral PFC, comprising of Brodmann Areas 44 and 45, which are also referred as the Broca's area, has been linked with language processing. In 1861, Paul Broca had presented a patient who could no longer pronounce more than a single syllable due to a brain lesion in the left frontal lobe [67]. This study demonstrated the role of the left inferior frontal lobe in the production of language. Later, the initial anatomical

model for the perception and production of language was propoed by Wernicke [68]. Despite many later changes, it is still roughly valid today [69].

One postmortem study that investigated the brain of a genius, who was able to speak at least 60 languages, revealed that the cytoarchitecture of Broca's area (Brodmann areas 44 and 45) were different when compared to the same regions of the control group. The conclusion drawn from this study is that different cytoarchitectonic characteristics of Broca's Area and excellence in language competence are probably associated with each other as observed from this subject [70].

The existence of BA 44 and 45 in the monkey ventrolateral frontal lobe suggests that this region may not be confined to the production of language but serving linguistic processes in a general manner [71]. The architectonic organization and the connections of BA 44 and 45 with other brain regions were observed to be quite distinct. For example BA 44 has connections with parts of the inferior parietal lobule, ventral premotor cortex, primary motor cortex, and bidirectional connections with frontal areas BA 45 and 47/12 and ventral area BA 9/46. BA 44 is thought to be capable of exercising control over the orofacial and hand/arm musculature due to its connectivity and position at the interface between prefrontal and premotor cortex, and thus can enable high-level control of different facets of communicative behavior expression [71].

On the other hand, BA 45 has linked with the superior temporal region and the nearby regions of the superior temporal sulcus. The region is thought to be crucial for active information regulation in posterior cortical association regions where short and long term coding of information is achieved. Neuroimaging studies have shown increased activation in left ventrolateral PFC while performing tasks that need retrieval of semantic information [72]. The mid-ventrolateral PFC (BA 45, 47/12) is observed to have a role during active information retrieval from the memory. Moreover, bilateral involvement has been reported; right hemisphere when nonverbal visual or visualspatial information is present and left hemisphere when the retrieval is verbal [71].

2.3.2 Frontopolar Cortex (Brodmann Area 10)

Brodmann Area 10 (BA10) is the most anterior part of the prefrontal cortex. The terms frontopolar cortex, frontopolar prefrontal cortex, rostral prefrontal cortex, anterior prefrontal cortex and the frontal pole are also used to refer to the BA10 area. This area is one of the least understood part of the human brain [73], attracting growing interest within cognitive neuroscience [74]. This region is believed to have a crucial role in human cognition due to the evolutionary expansion in its relative size compared with the chimpanzee brain. It is also larger in humans, both relatively and absolutely, compared to any other animal [75].

According to [76], at least three different cytoarchitectonic subregions exist. Distinct subregions within rostral PFC might be contributing to cognition differently in the way they operate or the behaviours or mental abilities afforded by them [74]. The meta-analysis provided in [73] shows signs of specialization regarding the functionality

inside the rostral PFC. Among lateral and medial regions of BA 10, functional variation has been observed as well as along the rostral–caudal dimension. Tasks that include mentalization, such as paying attention to the self and others emotions and mental states, are much likely to be correlated with activity in the medial rostral PFC than other tasks. Conversely, tasks involving working memory and episodic retrieval were linked with a higher rate of activity in the lateral rostral PFC. In addition to this lateral–medial specialization, functional specialization along the rostral–caudal dimension was found as well. Mentalizing was found to be correlated with the activity relatively in caudal subregions, whereas multitasking has been observed to be related with the activity more in rostral subregions [73].

According to Burgess & Wu [77], BA10 is activated when working on a high variety of cognitive tasks, ranging from simple to more complex tasks, including memory, judgment, or problem-solving. Some of the observed cognitive tasks are episodic retrieval of verbal and nonverbal information, language, semantic memory, motor and rule learning, nonverbal and verbal working memory, spatial memory, auditory perception, object processing, reasoning tasks, and intelligence tests. Furthermore, BA10 is thought to have a role in multitasking, prospective memory, metamemory, competence judgments, mentalizing, self-judgment, analogical reasoning, relational integration and so forth, which led to thinking of BA10 might be operating as a common system dealing with all these situations.

Burgess's "gateway hypothesis" [78] is an attempt to identify this common system proposing that BA10 is involved in the control of the direction of attention in which it selects attention either to stimulus-independent information (e.g. ,internal mental thoughts) or to stimulus-oriented information (e.g., stimuli received from the external world). Moreover, BA 10 with its lateral and medial parts, is thought to possess differing roles during these modes of attention [77, 61]. Stimulus-oriented (SO) attending happens when an individual's attentional focus is directed towards the external environment – one is simply "paying attention to" the things he or she sees or hears, etc. By contrast, stimulus-independent (SI) attending happens when an individual is caught up with the "thoughts in one's head", i.e., self-generated and/or maintained representations. Burgess proposed that at least some parts of rostral PFC exerts control over the degree to which one is in one of other mode of attending the "gateway hypothesis" [77] suggesting the region as a hub for "metacognition".

Regarding the functional connectivity of BA10, one meta-analysis study [79] has investigated the parallel activity of other brain regions while subregions of rostral PFC is active. Functional connectivity difference has been reported between lateral and medial areas of BA10. The lateral parts of RoPFC were found to be co-activated with the dorsolateral prefrontal cortex, dorsal anterior cingulate, lateral parietal cortex, and anterior insula; meanwhile medial parts of RoPFC was found to be co-activated with the temporal pole, posterior superior temporal sulcus and posterior cingulate.

Regarding connectivity patterns of the frontal cortex, BA 10 is observed to have links with both adjacent mid-ventrolateral prefrontal cortex (BA 47/12 and 45) and adjacent mid-dorsolateral prefrontal cortex (BA 9 and 46). Therefore, BA 10 is thought to subside in a perfect position to exert control over these regions. An example

engagement of BA 10 is with BA 46, enabling BA 10 in a position to be able to track the processes of monitoring taking place in the mid-dorsolateral prefrontal cortex. Monitoring of monitoring is referred as 'hyper-monitoring', and this capability makes the researchers think that BA 10 may be positioned at the highest level in the rostral–caudal hierarchy of lateral frontal control processes [62].

2.4 Competition and Cooperation

Executive functions and mentalizing capabilities are engaged in cooperation and competition, which are both essential to social interactions. According to the available data, social interactions entail a distinct set of cortical regions [80]. Both stances, for example, were shown to activate a common frontoparietal network that serves executive tasks, and the anterior insula, which is engaged in autonomic arousal. However, specific regions of the brain were shown to be selectively linked with cooperation and competition, including the orbitofrontal cortex in cooperation and the inferior parietal and medial prefrontal cortices in competition [80], and more research is needed to determine the relative contributions of these neural structures.

Research has revealed separate employment of ToM regions during cooperative situations or social games assessing cooperative intent [81, 82] as well as recruitment of ToM regions during competitive situations [83, 84]. Right and left temporoparietal junctions (rTPJ and lTPJ), precuneus, and dorsomedial prefrontal cortex are among these locations (DMPFC). Some theories anticipate that theory of mind (ToM) is recruited more for cooperation against competition or vice versa, whilst others suggest equivalent recruitment in both contexts. Although ToM areas were revealed to be activated similarly across interaction contexts [85], more medial prefrontal activity was seen for competition than cooperation [80].

In order to maintain both self and other game viewpoints, a competitive stance involves a mentalizing component as well as demands for higher executive processing. Evidence suggests that the medial prefrontal cortex is involved with a specific role in mentalizing. A class of large projection neurons, called spindle cells, are found exclusively in great apes and humans. These cells are hypothesized to be engaged in coordination of largely distributed brain activity affecting cognition and emotion [80]. Because its activation is routinely reported in neuroimaging research of attribution of intentions in a range of circumstances and activities, this region is largely believed to play a key role in theory of mind (ToM) [83].

CHAPTER 3

MATERIALS AND METHODS

3.1 Participants

48 healthy male participants (age range 19-47, M = 25.5, SD = 6.83) with right-hand dominance participated in the experimental study through the help of social media advertising to neighboring regions of METU. All participants were paired (24 total pairs), and their written informed consent was obtained before the experiment. Participants were given Edinburgh handedness test [86] and were also given the Turkish version of Experiences in Close Relationship (ECR) Scale [43] to identify subjects' attachment anxiety and avoidance scores before the experiment. 27 secure and 21 insecure participants were identified based on the resulting ECR scores (5 insecure-insecure, 11 secure-insecure, 8 secure-secure pairs were formed). Participants were paid according to their game score at the end of the experiment. The experiment was approved by the Middle East Technical University (METU) Human Subjects Research Ethics Committee (Figure 22 in Appendix A).



Figure 3: Photos of participants wearing the fNIRS sensor pads on their forehead before the experiment conducted at the M.E.T.U. Cognitive Science Lab

3.2 Experimental Procedure

The main goal of the experimental procedure was to enable participants to interact with each other face to face as in our daily lives without employing computer-based interaction. In order to facilitate naturalistic and standardized social interaction, dyads were asked to play variations of the well-known Rock-Paper-Scissors (RPS) game while facing each other and with their hands (i.e., not computerized).

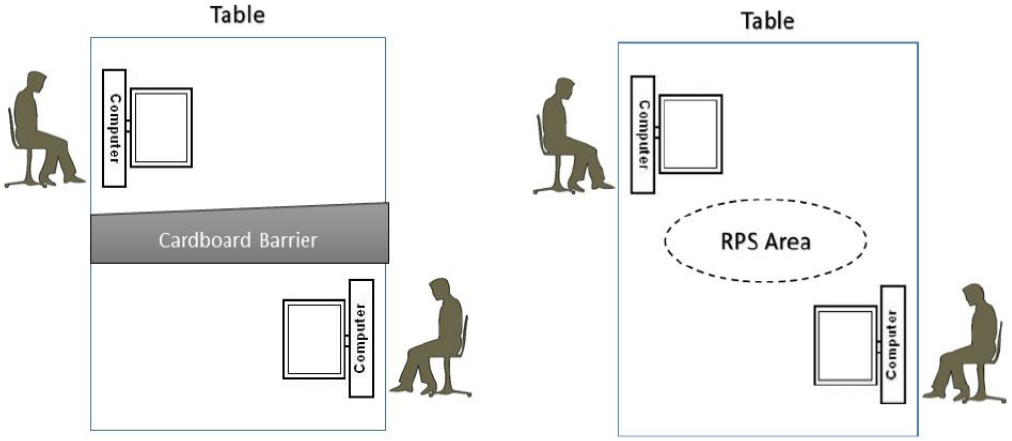


Figure 4: Left: Experiment setup during a solo task, Right: Experiment setup during a social task

Pairs of subjects were asked to carry out blocks of experimental tasks as individuals (solo) or together (social) as dyads. The illustrations of the experiment setup are provided in Figures 3, 4, and 5. Figure 3 illustrates the example installation of fNIRS devices on the forehead of participants while they sit on a chair. The participant dyads sit face to face having a table in front of them, and each participant has a computer visible only to them positioned on their left side. During the solo trials in which the participants play the RPS game by themselves, a cardboard barrier is placed in the middle of the table so that the participants cannot see each other, whereas during the social trials, the cardboard barrier is removed, and an area visible to both participants where they can play the RPS game with their right hands is revealed. Figure 4 shows the depiction of the experiment setup during the solo trials and the social trials, respectively. Lastly Figure 5 provides a photo of the actual setting of the experiment at the M.E.T.U. Cognitive Science Lab where participants are seen while playing the RPS game in a social trial and while resting in between trials.

Regular and reverse cooperative and competitive versions of the RPS game were introduced to reproduce various forms of social interaction. These tasks are variations of the RPS game, namely: “Competition-Normal”, “Competition-Reverse”, “Cooperation-Normal” and “Cooperation-Reverse”.



Figure 5: Photos of participants that illustrate the experiment setup in M.E.T.U. Cognitive Science Lab

- Competition-Normal: In order to obtain a competitive game, the well-known version of the RPS game is used, where for each round, the rules are; rock defeats scissors, scissors defeats paper, and paper defeats rock. Participants were instructed to play the well-known RPS game for 8 rounds by following the instructions displayed in their respective monitors. In this task, the goal is to compete with the other participant and try to win most of the RPS rounds.

- Competition-Reverse: Performing a well-known task compared to a novel task evokes lower levels of cognitive activity within the PFC. According to previous studies [87], when the goal is switched to losing the RPS task, even a stronger PFC response is detected with NIRS, possibly because this version of the game requires inhibition of behavior, which is one of the most important functions of the prefrontal cortex. For this purpose, a reverse RPS game where the goal is "to lose" to win was employed, which is called the competitive reverse RPS game. Competition- Reverse RPS game contains 8 RPS rounds in which for each round the rules are; scissors defeats rock, paper defeats scissors, and rock defeats paper. In this task, the goal is again to compete with the other participant and try to win most of the reverse RPS rounds. The participant who wins the most rounds was announced as that game's winner, and the other participant was announced as the loser of that game.

- Cooperation-Normal: In order to obtain a collaborative game, participants were asked to play the RPS game with the goal of selecting the same shape together at the end of the game round. As an example, both participants were expected

to show rock or scissors or paper together at the same time. If they show the same shape with their hands (for example both hands show rock), then both participants mutually win the game round, whereas if they show different shapes (for example, one hand showing rock but the other showing paper), then they both lose that round. To avoid participants from converging on the strategy of repeating the same shape all the time, they were instructed to show a different shape after each winning round. For example, if both participants show rock and win that round, then in the next round, their goal is to show either paper or scissors together. If they both show rock again, then that round is marked as a failure. In this task, the goal is to cooperate with the other participant and win most of the cooperative RPS rounds. The pair which won the most number of rounds together in the cooperative condition (cooperation-normal score plus cooperation-reverse score) was declared as the experiment's cooperative winner among all the teams that participated in the study.

- Cooperation-Reverse: In order to obtain a second kind of collaborative game, participants were asked to play the RPS game with the goal of this time not selecting the same shape together at the end of the game round. As an example, if one participant showed the rock, then the other participant had to show either the scissors or the paper at the same time. If they show different shapes with their hands, then both participants mutually win the game round, whereas if they show the same shapes, then they both lose that round. To avoid participants from converging on the strategy of repeating the same winning shapes, they were instructed to show a different shape after each winning round. For example, if one participant shows rock and the other shows paper in a winning round, then in the next round, each participant's goal would be to show different shapes from the previous winning round. If they both show the same shapes again, then that round is marked as a failure. In this task, the goal is again to cooperate with the other participant and win the most number of the cooperative reverse RPS rounds. The pair which won the most number of rounds together in the cooperative condition (cooperation-normal score plus cooperation-reverse score) was declated as the experiment's cooperative winner among all the teams that participated in the study.

The experiment consists of 1 practice block (Competition-Normal task) and then 8 blocks of experiment tasks (2 blocks of each kind of experimental task, in total 2x4). Each task block begins with a solo task, followed by a social task. The order of the blocks in the experiment was counterbalanced to reduce possible carry-on effects. The flow diagram in Figure 6 provides an example task order used during the experiment.

Prior to each block, the task for the following block was explained with the displayed instructions via the monitors in front of the participants. Within each task block, participants were asked to play first individually, and then with their partners where they completed 8 rounds of an RPS game variation each per block following the instructions on the monitor:

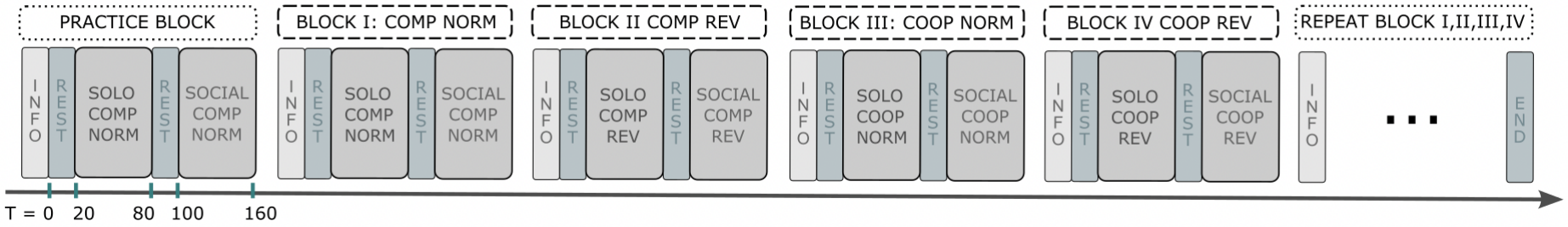


Figure 6: An example task flow for the experiment

- Solo part: Subjects play individually 8 rounds of the selected RPS task aligned with the instructions provided on the screen. During the solo task, subjects don't see each other playing (with the help of a cardboard barrier); however, they play the game synchronously. In this task, there is no winning or losing; subjects perform the same RPS operations, but they play with no one. This task is included in the experiment as a control case in order to check whether the coherence increase between subjects is simply due to performing the same movements together without any social connection or not.
- Social part: Subjects play 8 rounds of the selected RPS task with each other face to face (without the barrier) by following the instructions provided on the screen.

Each round lasted 7.5 seconds, making the total task duration 60 seconds. Within each block, there is one solo task and one social task, and a 20 second rest period before each task to let the participants cool down, allowing the measurements to be stabilized and synchronized again with the start of the next block. Overall, each block took 160 seconds to complete in total. The instructions provided at each round on the screen are illustrated in Figure 7. The instructions were provided in Turkish as follows; Ready (1.5 sec), 3 (0.5 sec), 2 (0.5 sec), 1 (0.5 sec), Go (2.5 sec), and Result (2 sec).

In an effort to motivate participants to perform well during competitive and cooperative conditions, they were instructed prior to the experiment that monetary prizes would be given based on their performance during competitive and cooperative rounds. Each pair completed a total of 4 blocks of competition tasks and 4 blocks of cooperation tasks. For each pair, 30 Turkish Lira (TL) was awarded to the participant who won the most number of trials during the 4 competitive rounds, and 20TL was awarded to the other participant. Moreover, to motivate the pairs' performance during the cooperation condition, a second monetary prize was offered for the team with the best score in the cooperation conditions. Pairs were informed prior to the experiment that they were to compete with the other pairs based on their overall cooperation performance and were instructed to maximize their overall cooperation scores so that the respective pair may win the cooperation prize (25TL for each subject of the winner pair). Competition and cooperation prizes were awarded to the winners upon the completion of all experiments.

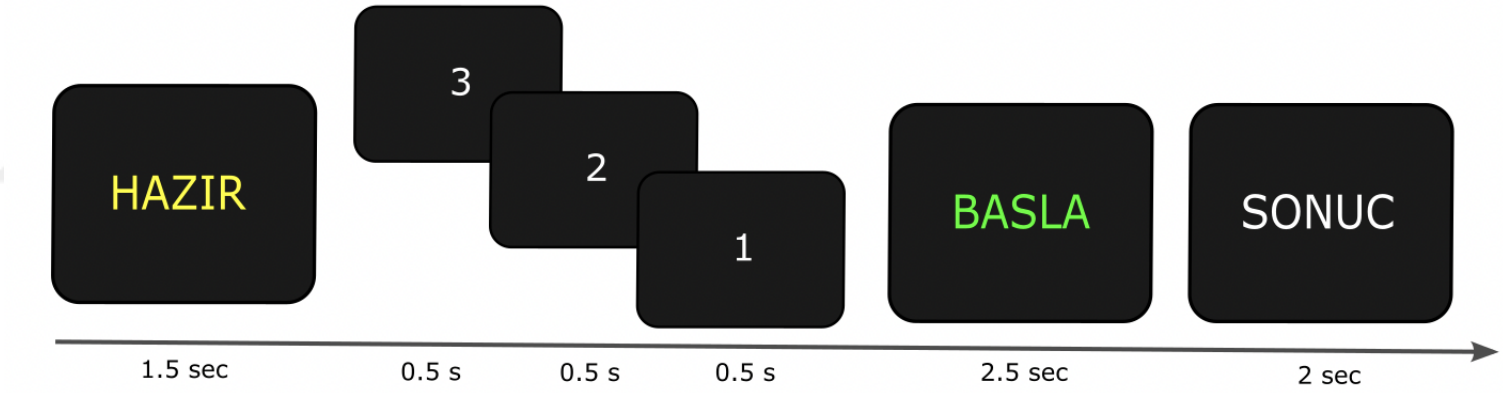


Figure 7: Instructions provided in each round to enable participants play RPS game synchronously

3.3 Data Acquisition

Functional near-infrared spectroscopy (fNIRS) imaging was utilized to measure local changes in cerebral haemodynamic activity, which is then used to infer neural activity within the PFC. The brain is dependent on the supply of blood to function and contains neurovascular control mechanisms that assure that the blood supply of the brain is commensurate to the energy needs of its cellular constituents [88]. This mechanism is called neurovascular coupling, which indicates the existing link between neural activity and the local change in cerebral blood flow (CBF), such that an increase in neural activity is accompanied by an increase in CBF around the activated area, which is temporally linked to the period of activation, providing additional glucose and oxygen to the active neurons in that region. Given that the increase in CBF is significantly higher than the corresponding oxygen consumption, the resulting effect leads to the haemodynamic response, which is a net increase in the amount of oxygenated haemoglobin (HbO) and a net decrease of deoxygenated haemoglobin (HbR) [89].

fNIR technology uses an optical apparatus that includes light sources and light detectors. The light sources radiate specific wavelengths of light on the tissue, which is then received by the light detectors after its interaction with the tissue. The light in the near-infrared range between 700 to 900 nm is capable of penetrating most of the biological tissues surrounding the cerebral cortex. Within this optical window, the absorbance of the main constituents in the human tissue, such as water, melanin, and other lipids, is smaller than the absorbance characteristics of HbO and HbR [90]. The photons in this optical window are either scattered by different layers of the head or absorbed mainly by HbO and HbR, which is linked to tissue oxygenation. A photodetector placed at a certain distance away from the light source can collect the photons that are not absorbed by the targeted chromophores, which travel along a banana-shaped path between the source and detector due to scattering [91]. The change of the reduction in the intensity of the photons detected by the light detectors is assumed to be due to the changes in absorption resulting from the variation in the concentrations of HbO and HbR in the brain tissue since attenuation caused by scattering is constant with respect to cognitive activity [92]. Therefore, changes in the relative ratios of HbO and HbR during brain activity can be measured. Haemoglobin is only present in the red blood cell, and its oxygenated state is, therefore, an indicator of blood oxygenation. Using the modified Beer-Lambert Law [93, 94] changes in cerebral haemodynamic activity can be estimated.

Functional near-infrared spectroscopy (fNIRS) imaging device utilized in this study is shown in Figure 8, which is developed at Drexel University, manufactured and supplied by fNIR Devices LLC [95]. The system can monitor changes in relative concentrations of oxy- and deoxy-hemoglobin at a temporal resolution of 2 Hz utilizing an LED-based sensor pad which allows a naturalistic experiment environment by covering only the forehead of the participant. The sensor pad holds 4 light sources and 10 detectors and has a 2.5 cm source-detector separation allowing for approximately 1.25 cm penetration depth. This device can monitor hemodynamic changes occurring along a rectangular grid covering the forehead region, which corresponds to 16 measurement

locations or optodes that fall within Brodmann areas 9, 10, 46, 45 and 44 (Figure 8). The system also includes a control module with integrated power supply for sensor control and data acquisition, and a desktop computer for the data analysis software (COBI Studio) [96].

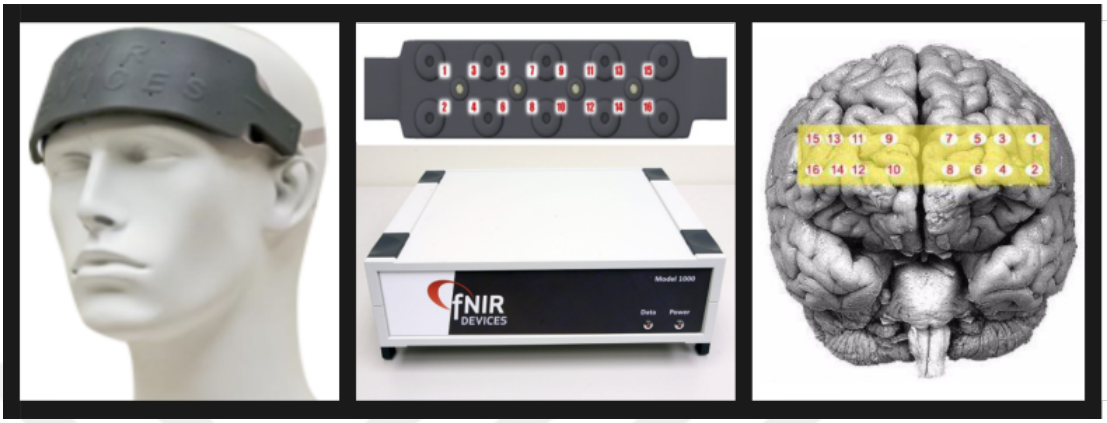


Figure 8: Left: Installation of the fNIRS sensor pad on the forehead. Middle: The sensor pad and the unit for data acquisition. Right: The anatomical positions for the 16 optodes

In this study, the hyperscanning technique was used where HbO changes in the prefrontal cortices of the dyads were captured simultaneously and in a synchronized manner using two identical fNIRS devices attached to each participant. In order to achieve synchronization during hyperscanning, participants were asked to follow each task round initiation and ending signaled through an OpenSesame [97] based experiment program displaying instructions synchronously on their computer screens. Labels to fNIRS signals indicating the initiation and the end of each round were automatically added via scripts that triggered time synchronization markers within the experiment software.

3.4 Data Analysis

Raw light intensity measurements and marker files were analyzed by using the fnirSoft software [98]. For each optode belonging to each subject, raw data signal was first visually inspected, and signals showing signs of saturation, measurement failure, and excessive noise such as motion artifacts were identified and discarded from further processing.

Using fnirSoft, raw light intensity signals were first low pass filtered with an FIR filter with order 20 and cut off frequency 0.1 to attenuate cardiac effects. Changes in the relative concentrations of oxy-hemoglobin (HbO) were calculated over the filtered data in reference to baseline obtained at rest by employing the modified Beer-Lambert Law. Afterward, first-order linear detrending is applied to the HbO data. Output data files were exported as Matlab files for further processing.

3.4.1 Wavelet Transform Coherence

Wavelet Transform Coherence (WTC) is a method that can be used for examining relationships between two time series data. It measures the cross-correlation between two time series as a function of frequency and time [99] and has been utilized in previous fNIRS hyperscanning studies [9, 10, 27]. In this study, WTC was used similarly to assess the relationship between the fNIRS signals obtained from a pair of participants during a hyperscanning experiment.

Unlike traditional mathematical methods, such as Fourier analysis which examines periodicities in the frequency domain, wavelet transforms can provide the frequency of the signals and the time associated with those frequencies, enabling the discovery of localized intermittent periodicities. There are two classes of wavelet transforms; the Continuous Wavelet Transform (CWT) and Discrete Wavelet Transform (DWT). While DWT is useful for noise reduction and data compression, the CWT is better for feature extraction purposes. From two CWTs, the WTC can be calculated, which can be thought of as the local correlation between the time series in time-frequency space, to uncover locally phase-locked behavior [99].

A wavelet is a function with zero mean, localized in both frequency and time, and can be characterized by how localized it is in time (Δt) and frequency (Δw). When using wavelets for feature extraction purposes, the Morlet wavelet (with $\omega_0 = 6$) is a good choice. Morlet wavelet is mathematically identical to a short-time Fourier transform using a Gaussian window function, which is defined as

$$\psi_0(\eta) = \pi^{\frac{-1}{4}} e^{i\omega_0\eta} e^{\frac{-1}{2}\eta^2} \tag{1}$$

where ω_0 is dimensionless frequency and η is dimensionless time. The idea behind the CWT is to apply the wavelet as a band-pass filter to the time series. The CWT of a time series ($x_n, n = 1, ..., N$) with uniform time steps δt, is defined in [99] as the convolution of x_n with the scaled and normalized wavelet:

$$W_n^X(s) = \sqrt{\frac{\delta t}{s}} \sum_{n'=1}^{N} x_{n'} \psi_0 \Big[(n' - n) \frac{\delta t}{s} \Big] \tag{2}$$

From two CWTs the WTC can be calculated which is defined as the square of the cross-spectrum normalized by the individual power spectra. This gives a quantity between 0 and 1, and measures the cross-correlation between two time series as a function of frequency [100]. Following this, [99] has defined the wavelet coherence of two time series as:

$$R_n^2(s) = \frac{\Big| S\big(s^{-1} W_n^{XY}(s)\big) \Big|^2}{S\Big(s^{-1} \big|W_n^X(s)\big|^2\Big) . S\Big(s^{-1} \big|W_n^Y(s)\big|^2\Big)} \tag{3}$$

where S is a smoothing operator. For more details, please refer to [99] and [100].

3.4.2 Calculation of WTC Results

Crosswavelet and wavelet coherence software were provided by A. Grinsted as a MATLAB package reachable from the website ([101]. For every pair, two continuous synchronized HbO signals that belong to subjects within each pair were provided as input to the WTC function, which produced WTC plots as well as WTC measures between 0 and 1 as output. An example WTC plot is shown in Figure 10.

Brain-to-brain interactions were assessed specific to the rest and task blocks by calculating the wavelet transform coherence (WTC) increase between two brain signals that belong to subjects within each pair. The temporal resolution for fNIRS devices in the experiment was 2 Hz. In the WTC graphs, the horizontal axis reflects the time course of the experiment with 2 Hz sampling rate, and the vertical axis reflects the period that corresponds to frequency values depicted in Table 1.

Table 1: WTC periods, their corresponding frequency range, and task duration in seconds for 2 Hz sampling rate

Period:	2	4	8	16	32	64	128	256
Task duration:	1s	2s	4s	8s	16s	32s	64s	128s
Frequency:	1	0.5	0.25	0.125	0.0625	0.03125	0.015625	0.0078125

The experiment consisted of solo and social tasks, each having 8 RPS rounds lasting 7.5 seconds, making a total of 60 seconds for task duration. Within each block, there is one solo task and one social task, and a 20 second rest period before each task. For each optode that belongs to each pair, inter-brain synchrony values between the periods of 64 and 128 were computed, which corresponds to a duration between 32 and 64 seconds, covering the 60 seconds long task duration sampled at a temporal resolution of 2 Hz. Mean coherence values for the rest and task blocks were calculated for further coherence increase analysis, which only includes the values from blocks of signals that were not discarded due to saturation, measurement failure, and noise artifacts. Table 2 illustrates the example mean HbO WTC values for Competition-Normal-I task for each optode that belongs to the first four subject pairs. Mean coherence values for every rest and task block were calculated for further coherence increase analysis.

HbO concentration changes that belong to the first optode of the subjects from the 4th pair are shown in Figure 9, and the WTC plot is shown in Figure 10 for the same pair. The WTC graph shows the regions with high wavelet coherence in red color and the regions with low wavelet coherence in blue color as indicated on the right-hand side of the figure. Periods 64 and 128 were marked with white lines on the WTC graphs to show coherence values for task blocks which were 60 seconds long. According to timing values derived from the fNIRS marker output file and fnirSoft, task blocks

Table 2: Mean HbO WTC values for the Competition-Normal-I task for each optode that belong to the first four subject pairs

Optode #	Pair: 1	Pair: 2	Pair: 3	Pair: 4
1	.2304	.2483	.2246	.8508
2	.3506	.2887	.4033	.5562
3	.2570	.0874	.1490	.6099
4	.4798	.1855	.2866	.3352
5	.5592	.1512	.2716	.7572
6	.5653	.2702	.1713	.4015
7	.6003	.1225	.2170	.6829
8	.3757	.2211	.2651	.1304
9	.5646	.2984	.1774	.7661
10	.2560	.1467	.3321	.5131
11	.5657	.4884	.2030	.6395
12	.3326	.3919	.2413	.2603
13	.0857	.2128	.1785	.5965
14	.1551	.2125	.2994	.5002
15	.1662	.3780	.1469	.5388
16	.1636	.4702	.1441	.6835

were marked with white color within the period interval on the WTC graphs as well according to the following labels:

- White '——': Social Competition Normal
- White '- - -' : Social Competition Reverse
- White '. . . . . .': Social Cooperation Normal
- White '- . - .': Social Cooperation Reverse
- Magenta '——': Solo Competition Normal
- Magenta '- - -' : Solo Competition Reverse
- Magenta '. . . . . .': Solo Cooperation Normal
- Magenta '- . - .': Solo Cooperation Reverse

The statistical significance level of the wavelet coherence is estimated using Monte Carlo methods. Significant high coherence regions in WTC plots are shown with a black contour line around the region. In addition, a Cone of Influence (COI) takes place in the plot as a transparent white region of cone, indicating the edge effects.

For each optode that belong to each pair, WTC coherence values were extracted by using HbO data. Mean coherence values during rest and solo/social tasks were

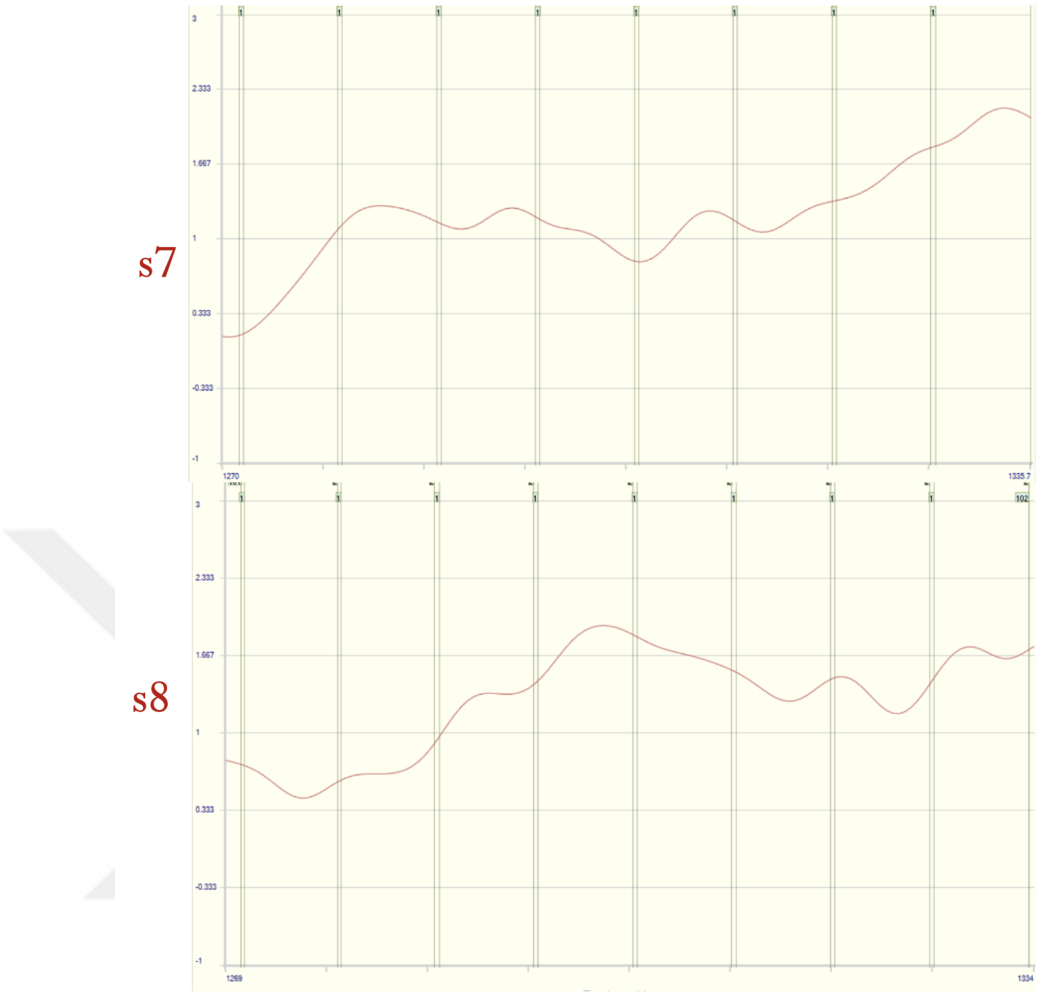


Figure 9: HbO concentration changes that belong to the first optodes of subjects forming the 4th pair (Up: Subject #7 of Pair 4. Down: Subject #8 of Pair 4).

calculated for each optode and pair for the first and second turns of Competition-Normal, Competition-Reverse, Cooperation-Normal, and Cooperation-Reverse tasks. Then inter-brain coherence increase measurements were conducted utilizing the mean WTC results as explained in the following subsection.

3.4.3 Inter-brain Coherence Increase Measurement Methods

In order to understand the effects of only social measures within the PFC, inter-brain coherence increase were assessed in four measurement methods as shown in Table 3, in which measurement types C and D can be considered as the novel coherence increase measures introduced by this study:

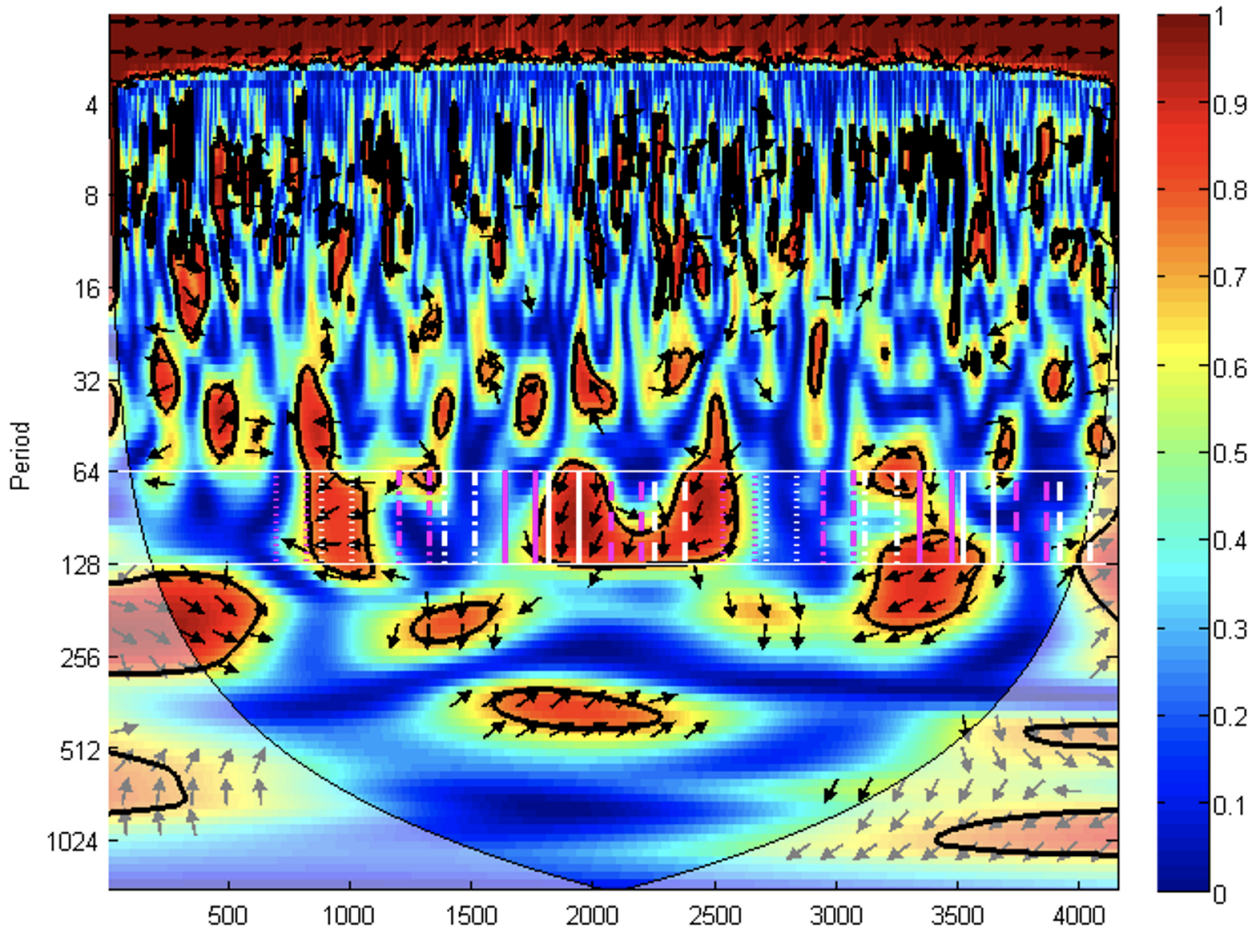


Figure 10: WTC plot of the 4th pair

Table 3: Inter-brain coherence increase measurement methods utilized in this study

Type	Name	Calculation
Type A	“Solo task coherence increase”	(Mean coherence of solo task) – (Mean coherence of prior rest period)
Type B	“Social task coherence increase”	(Mean coherence of social task) – (Mean coherence of prior rest period)
Type C	“Social coherence difference”	(Mean coherence of social task) – (Mean coherence of solo task)
Type D	“Social coherence increase difference”	Type B - Type A

- Type A (Solo - Rest) Inter-brain Coherence Increase: Type A coherence increase means that there is inter-brain coherence among participants while they perform the specified task individually without having visual contact with each other. Significant coherence increase in the solo task shows that the coherence increase is not due to socialization but due to the nature of the task (e.g., motor actions such as arm movements and hand gestures). Therefore, it is important to ensure that there is no Type A (solo task) coherence in regions where increased coherence is expected due to the social nature of the task.

- Type B (Social - Rest) Inter-brain Coherence Increase: Type B coherence increase measure is used in previous studies and means that there is inter-brain coherence among participants while they perform the specified task together socially having visual contact with each other. Significant coherence increase in such conditions shows that there is coherence increase due to the social task performed. However, we believe that this type of coherence increase should be assessed together with Type A coherence increase values to ensure that the coherence increase is not due to the nature of the task alone without social means.

- Type C (Social - Solo) Inter-brain Coherence Difference: Type C coherence increase is a novel measure of coherence increase introduced in this study and means that there is inter-brain coherence difference among participants while they perform the specified task socially and individually. Significant positive coherence difference shows that there is significantly better coherence during the social task compared to its solo version. This new coherence increase measurement directly measures the coherence increase effect of socialization since it is the only difference introduced between a social task and a solo task. Therefore a significant finding in this measurement can identify the social ingredients of brain interworking.

- Type D (Type B – Type A) Inter-brain Coherence Increase Difference: Type D coherence increase is a novel measure of coherence increase as well which means that there is inter-brain coherence increase difference among participants while they perform the specified task socially and individually. Significant positive coherence increase difference shows that there is significantly better coherence during the social task compared to its solo version. This new coherence increase measurement focuses on the coherence increase difference of socialization since it is the only difference introduced between a social task and a solo task.

Along with inter-brain coherence increase analysis, attachment style effects have been investigated on 27 secure and 21 insecure (17 anxious, 2 avoidant, 2 disorganized) participants' data by analyzing differences of the HbO mean concentration changes at regions of the prefrontal cortex. Significant differences have been investigated by employing 2-sample t-tests among HbO activation levels of secure and insecure participants with respect to both baseline and prior rest periods. Moreover, to understand whether attachment styles affect coherence during social interaction, differences regarding the coherence of pairs having both subjects classified with the same attachment styles and pairs with different attachment styles were investigated.

For this purpose, Secure – Insecure and Secure – Secure participant groups' differences were analyzed.

CHAPTER 4

RESULTS

4.1 Activation Analysis

4.1.1 Activation Significance w.r.t. Competition and Cooperation

Mean HbO concentration changes were calculated for all tasks in reference to rest periods preceding each task. One sample t-test was employed to identify those optodes where statistically significant mean HbO concentration changes occurred. False Discovery Rate (FDR) correction was employed on the t-tests to control the familywise error rate for multiple comparisons [102]. Significant changes in HbO concentration levels were observed during the social tasks, including task-specific increases (see Figure 11 and Table 4) and decreases (see Figure 12 and Table 5) at certain PFC regions. Since each condition was repeated twice in the experiment, the first and second exposures were analyzed separately to explore changes in HbO responses due to familiarization and/or learning effects.

Table 4: Significant one-sample t-test results for positive mean HbO concentration changes (activation) w.r.t. prior rest period for all tasks. The optodes that have passed FDR correction are shown in bold font.

Optode #	Social Task	T-statistic (df)	P-value	Effect size: r
Opt 2	**Coop-Norm-I**	**t (37) = 3.6445**	**.001**	**.513**
Opt 2	Coop-Rev-I	t (36) = 2.3212	.026	.360
Opt 3	Comp-Norm-I	t (36) = 2.1920	.035	.343
Opt 3	Coop-Norm-I	t (36) = 2.0438	.048	.322
Opt 4	Comp-Norm-I	t (38) = 2.3289	.025	.353
Opt 4	Comp-Rev-I	t (38) = 2.0727	.045	.318
Opt 4	**Coop-Norm-I**	**t (38) = 3.1737**	**.003**	**.457**
Opt 4	Coop-Rev-I	t (37) = 2.1421	.039	.332
Opt 4	Coop-Norm-II	t (33) = 2.1749	.037	.354
Opt 14	Comp-Norm-I	t (39) = 2.1985	.034	.332
Opt 14	**Coop-Norm-I**	**t (39) = 3.3691**	**.002**	**.474**
Opt 14	Coop-Rev-I	t (38) = 2.2317	.032	.340
Opt 16	Coop-Norm-I	t (38) = 2.5622	.014	.383

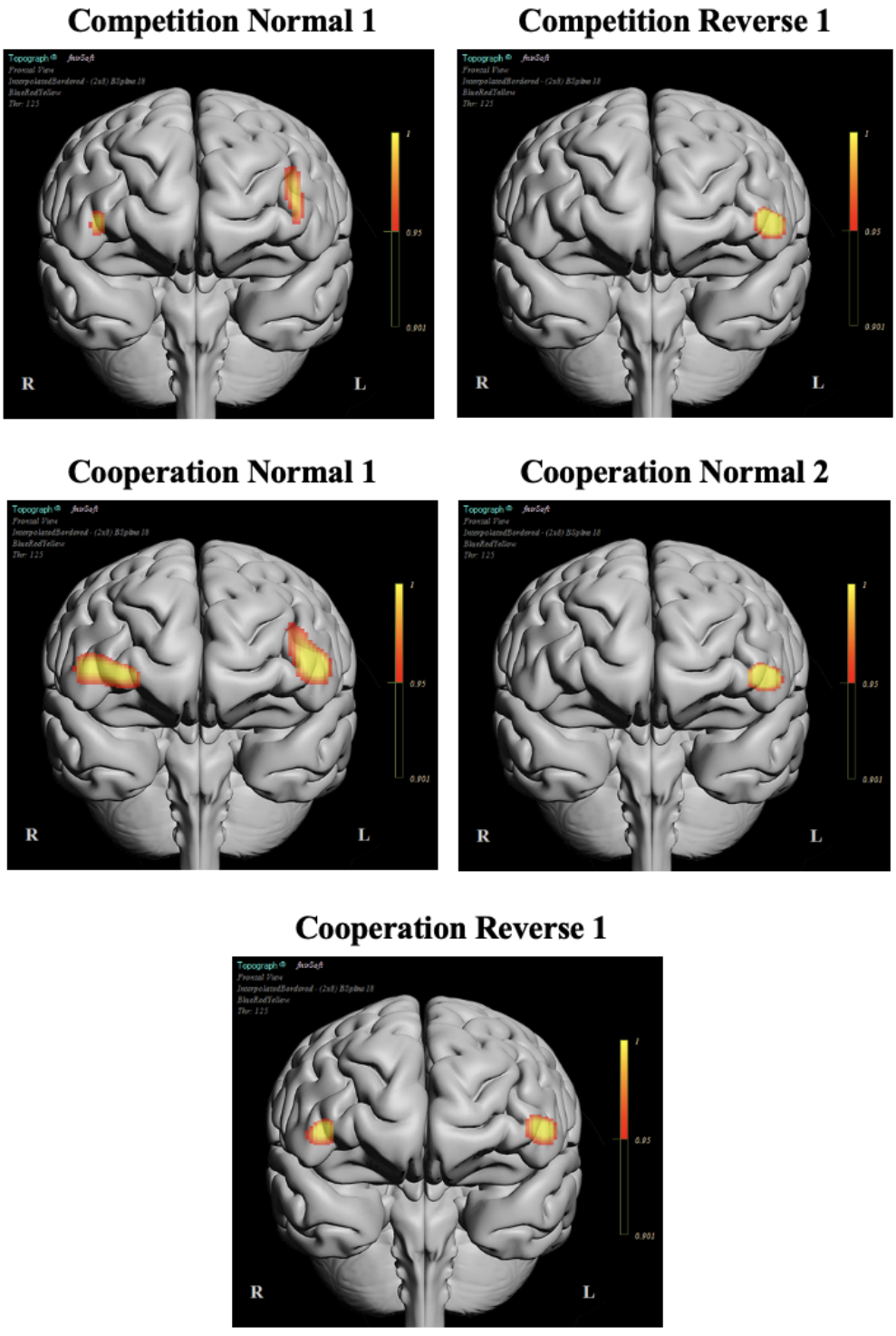


Figure 11: The PFC locations where significant positive mean HbO concentration changes were observed for all social tasks

These findings show significant HbO increase at bilateral DLPFC regions during both competition and cooperation tasks, especially during the initial trials. For the regular initial cooperation task, significant HbO increase was observed in Optode 2 ($p<0.01$), Optode 3 ($p<0.05$), Optode 4 ($p<0.01$), Optode 14 ($p<0.01$) and Optode 16 ($p<0.05$) which correspond to bilateral DLPFC regions. The learned (second) cooperation normal task was observed to elicit significant activation in only Optode 4 ($p<0.05$) over the left DLPFC. Similar to the regular cooperation task, the reverse cooperation task was observed to elicit significant HbO response bilaterally at optodes 2 ($p<0.05$), 4 ($p<0.05$), and 14 ($p<0.05$), but only for the initial task.

Significant bilateral DLPFC activation was observed during the initial competition tasks as well. For the normal competition task, significant HbO responses were observed at Optode 3 ($p<0.05$), Optode 4 ($p<0.05$), and Optode 14 ($p<0.05$). The reverse initial competition task was observed to elicit significant activation only at Optode 4 ($p<0.05$), which corresponds to the left DLPFC.

Table 5: Significant one-sample t-test results for negative mean HbO concentration changes w.r.t. prior rest period for all tasks

Optode #	Social Task	T-statistic (df)	P-value	Effect size: r
Opt 9	Comp-Norm-II	t (36) = -2.6150	.013	.399
Opt 10	Comp-Norm-II	t (28) = -2.7876	.009	.466
Opt 10	Comp-Rev-II	t (28) = -3.1810	.003	.515
Opt 11	Comp-Norm-II	t (37) = -2.0949	.043	.325
Opt 12	Comp-Rev-II	t (31) = -2.1363	.040	.358
Opt 15	Comp-Rev-II	t (31) = -2.6078	.013	.424

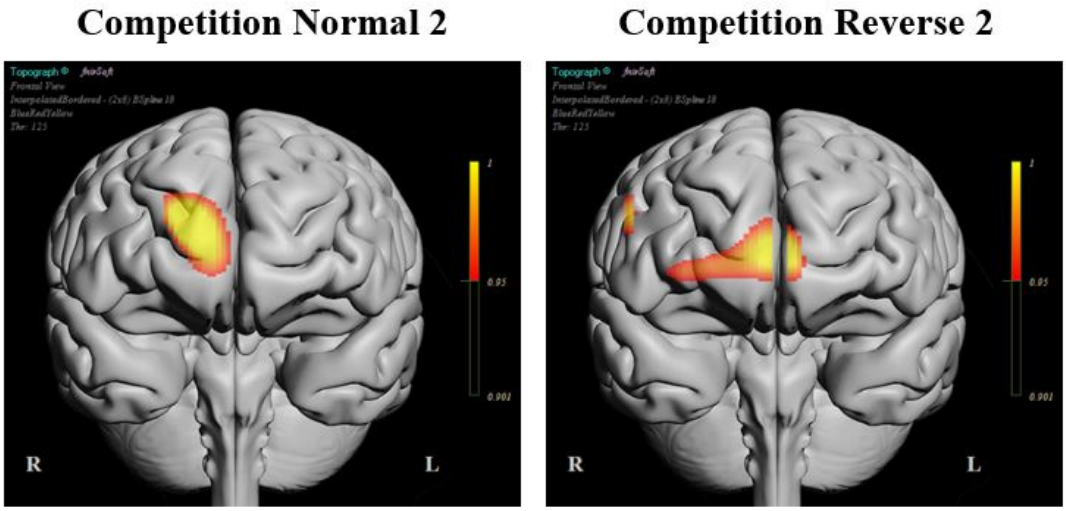


Figure 12: The PFC locations where significant negative mean HbO concentration changes were observed for all social tasks

On the other hand, during the learned (second) competition tasks, a significant decrease in HbO concentration was observed. The decreasing trends were most prominent at the right frontopolar cortex during both normal and reverse second competition tasks and at the right DLPFC during the reverse second competition task. For the second normal competition task, a significant decrease in HbO levels was observed at Optode 9 ($p<0.05$), Optode 10 ($p<0.01$), and Optode 11 ($p<0.05$), which correspond to the right frontopolar cortex. Likewise, a significant decrease in HbO levels was observed at Optode 10 ($p<0.01$), Optode 12 ($p<0.05$), and Optode 15 ($p<0.05$) during the second reverse competition task, which corresponds to the right frontopolar cortex and right DLPFC.

4.1.2 Competition vs. Cooperation

Regarding the differences between competition and cooperation social tasks, mean HbO levels were compared for each type of social task. Overall mean HbO concentration changes for the competition tasks were subtracted from the overall mean HbO concentration changes for the cooperation tasks with respect to respective prior rest periods. As shown in Figure 13, mean HbO concentration changes for cooperation minus mean HbO concentration changes for competition results in positive values in most of the Optodes, implying cooperation RPS tasks lead to higher levels of increase in haemodynamic activity within PFC in general compared to competition RPS tasks.

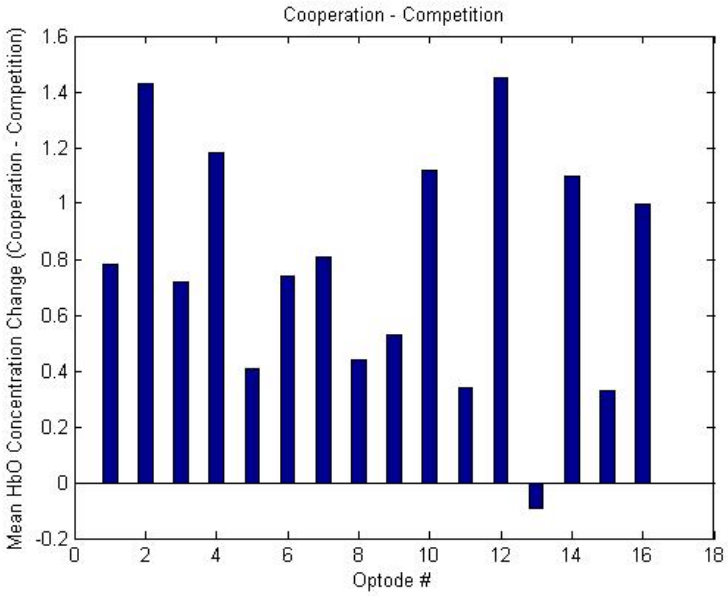


Figure 13: Mean HbO concentration changes for all cooperation tasks minus mean HbO concentration changes for all competition tasks with respect to prior rest period.

4.2 Inter-brain Coherence

4.2.1 Inter-brain Coherence Increase Results

In order to identify those optodes that exhibit significant coherence increase during different forms of solo and social tasks, one-sample t-tests were employed for every type of coherence increase computation at the group level. T-test calculations were performed on only the eligible data for that optode and task. One-sample t-test results for the competition tasks are summarized in Table 6 and illustrated in Figure 14. The results for cooperation normal and reverse tasks are summarized in Table 7 and Table 8 and also illustrated in Figure 15 and Figure 16 respectively. The letters with the red font on top right corner indicate the coherence increase measurement type, such as C means Type C. Significant coherence values were depicted with color codes ranging from red to yellow at the corresponding region. As the color gets closer to red, the p value (of the one-sample t-test) gets closer to the critical alpha level 0.05. On the other hand, as the color gets closer to yellow, the p value gets closer to 0, indicating very high significance.

Table 6: One-sample t-test results for the competition tasks. The optodes that have passed the FDR correction are shown in bold font.

Optode #	Social Task	Type	T-statistic (df)	P-value	Effect size: r
Opt 2	Comp-Norm-II	A	t (13) = 1.9097	.039	.468
Opt 2	Comp-Rev-II	B	t (13) = 1.8258	.045	.451
Opt 2	**Comp-Rev-II**	**C**	**t (13) = 3.6976**	**.001**	**.715**
Opt 6	Comp-Rev-II	C	t (10) = 2.3207	.021	.591
Opt 9	**Comp-Norm-I**	**C**	**t (14) = 3.0845**	**.004**	**.636**
Opt 11	Comp-Norm-I	C	t (14) = 2.3463	.017	.531
Opt 14	**Comp-Norm-I**	**C**	**t (15) = 2.8590**	**.006**	**.593**
Opt 16	Comp-Norm-II	A	t (13) = 2.2938	.019	.536

Competition task results summarized in Table 6 and Figure 14 show that both normal and reverse competition tasks elicit significant coherence increase in Type B and C measurement types. During the initial normal competition task, Optodes 9 ($p<0.01$), 11 ($p<0.05$), and 14 ($p<0.01$) were identified as having significant positive inter-brain coherence difference in Type C measurement, which correspond to the right DLPFC and the frontopolar cortex. On the other hand, for the second reverse competition tasks, Optode 2 in Type B ($p<0.05$) and Optodes 2 ($p<0.01$) and 6 ($p<0.05$) in Type C measurement were identified as having significant positive inter-brain coherence difference, which corresponds to the left DLPFC. These results also reveal lateralized coherence difference in DLPFC for competition tasks depending on the regular or reverse version of the task.

Moreover, Type A significant coherence increase in Optode 2 ($p<0.05$) and Optode 16 ($p<0.05$) was observed during the second competition normal task. Solo tasks were

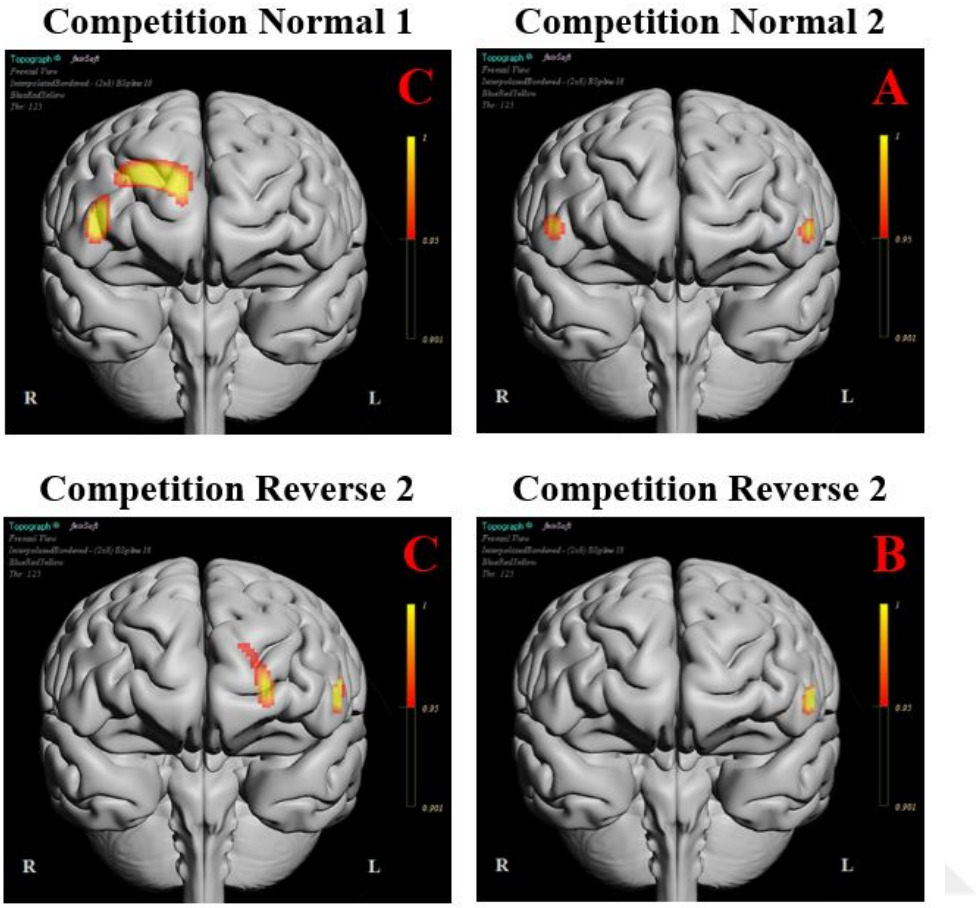


Figure 14: The PFC locations where significant coherence increase were observed for competition tasks

the same throughout the experiment, such that the participants have played the RPS game by themselves without competitive or cooperative intents prior to each social task. In other words, the solo tasks, regardless of their naming, were exactly the same as other solo tasks; however, Type A significant coherence increase was observed only during the solo task prior to the second competition normal task.

Similar to the competition tasks, significant coherence increase in normal and reverse cooperation tasks were also observed, depending on the nature of the task. As shown in Table 7 and Figure 15, during the initial normal cooperation task, Optodes 7 ($p<0.05$) and 16 ($p<0.05$) were identified as having significant positive inter-brain coherence difference only in Type C measurement, which corresponds to the right DLPFC and the left frontopolar cortex. For the second (learned) cooperation normal tasks, Optodes 11 ($p<0.05$) and 16 ($p<0.05$) in Type B measurement, Optodes 9 ($p<0.05$), 11 ($p<0.01$) and 15 ($p<0.05$) in Type C measurement and Optodes 9 ($p<0.05$), 11 ($p<0.01$) and 16 ($p<0.05$) in Type D measurement were identified as optodes exhibiting significant positive inter-brain coherence differences, which corresponds to the right DLPFC and FC.

Table 7: One-sample t-test results for the cooperation normal tasks

Optode #	Social Task	Type	T-statistic (df)	P-value	Effect size: r
Opt 7	Coop-Norm-I	C	t (10) = 2.2637	.023	.582
Opt 9	Coop-Norm-II	C	t (12) = 2.4084	.016	.570
Opt 9	Coop-Norm-II	D	t (12) = 1.8723	.042	.475
Opt 11	Coop-Norm-II	B	t (12) = 2.0436	.031	.508
Opt 11	Coop-Norm-II	C	t (12) = 2.7209	.009	.617
Opt 11	Coop-Norm-II	D	t (12) = 2.9019	.006	.642
Opt 15	Coop-Norm-II	C	t (7) = 2.0995	.037	.621
Opt 16	Coop-Norm-II	B	t (12) = 1.8420	.045	.469
Opt 16	Coop-Norm-II	D	t (12) = 1.9533	.037	.491
Opt 16	Coop-Norm-I	C	t (15) = 1.9692	.033	.453

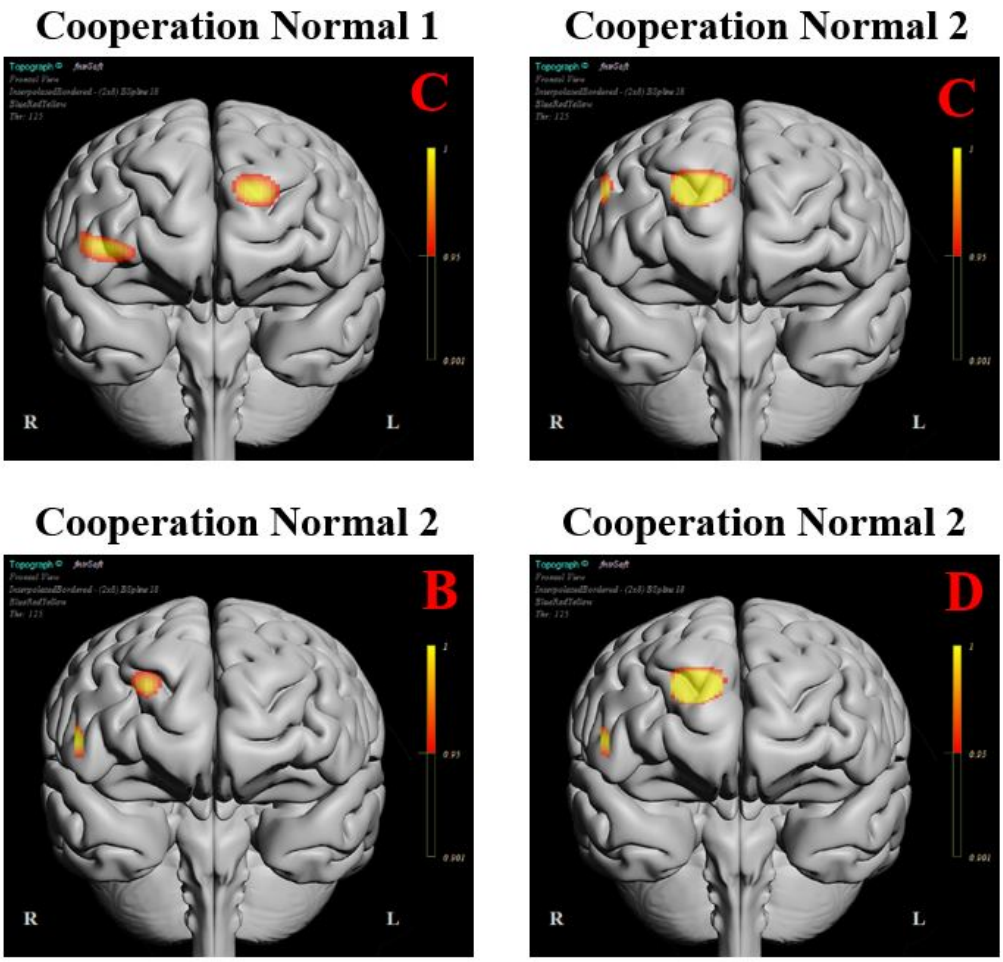


Figure 15: The PFC locations where significant coherence increase were observed for the cooperation-normal tasks

Table 8: One-sample t-test results for the cooperation reverse tasks

Optode #	Social Task	Type	T-statistic (df)	P-value	Effect size: r
Opt 1	Coop-Rev-I	B	t (13) = 1.9465	.036	.475
Opt 1	Coop-Rev-I	D	t (13) = 1.9308	.037	.472
Opt 1	Coop-Rev-II	D	t (10) = 2.1317	.029	.558
Opt 2	Coop-Rev-I	B	t (13) = 2.2559	.021	.530
Opt 2	Coop-Rev-I	D	t (13) = 1.8194	.046	.450
Opt 2	Coop-Rev-II	D	t (12) = 1.9059	.040	.482
Opt 3	Coop-Rev-I	B	t (14) = 2.8317	.006	.603
Opt 3	Coop-Rev-I	C	t (14) = 2.4650	.013	.550
Opt 3	Coop-Rev-I	D	t (14) = 2.6188	.010	.573
Opt 3	Coop-Rev-II	D	t (12) = 1.8797	.042	.476
Opt 7	Coop-Rev-I	C	t (10) = 2.9733	.007	.685
Opt 9	Coop-Rev-I	C	t (13) = 2.1387	.026	.510
Opt 10	Coop-Rev-I	C	t (7) = 2.4735	.021	.682
Opt 11	Coop-Rev-I	C	t (13) = 2.0259	.031	.489

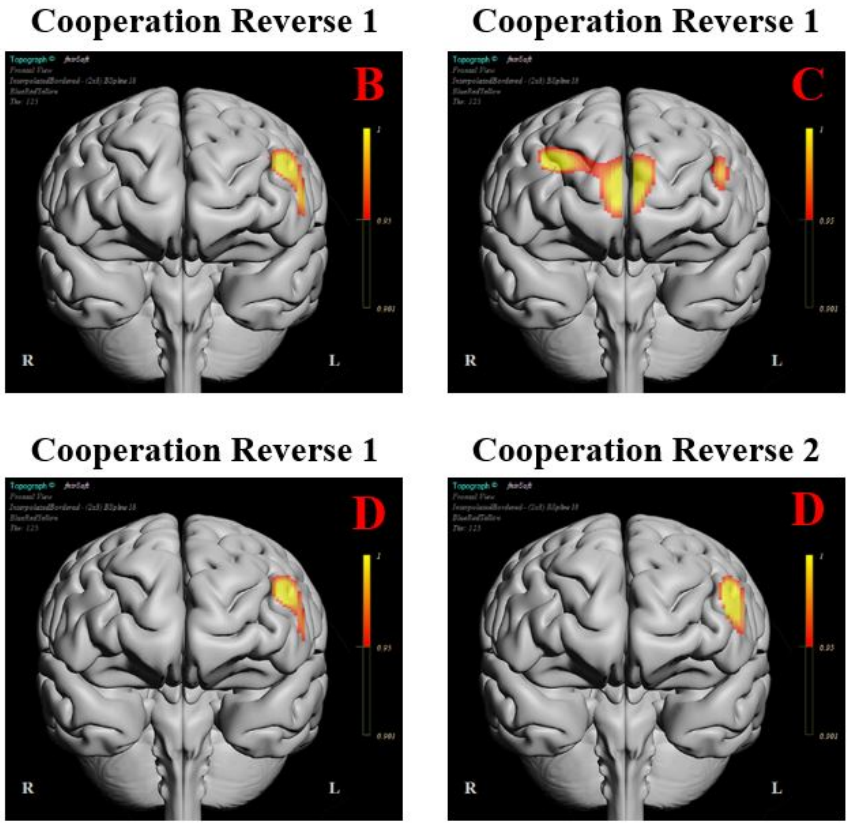


Figure 16: The PFC locations where significant coherence increase were observed for the cooperation reverse tasks

On the other hand, for the reverse cooperation tasks, initial and second tasks elicit significant coherence increase in similar PFC regions as depicted in Table 8 and Figure 16. During initial reverse cooperation task, Optodes 1 ($p<0.05$), 2 ($p<0.05$) and 3 ($p<0.01$) in Type B measurement, Optodes 3 ($p<0.05$), 7 ($p<0.01$), 9 ($p<0.05$), 10 ($p<0.05$) and 11 ($p<0.05$) in Type C measurement and Optodes 1 ($p<0.05$), 2 ($p<0.05$) and 3 ($p<0.01$) in Type D measurement were identified as having significant positive inter-brain coherence difference, which corresponds to the left DLPFC for Type B and D and in addition frontopolar cortex for Type C. For the second (learned) tasks, Optodes 1 ($p<0.05$), 2 ($p<0.05$), and 3 ($p<0.05$) were identified as having significant positive inter-brain coherence difference only in Type D measurement, which corresponds to the left DLPFC similar to the initial task findings.

4.2.2 Coherence Increase vs. Cooperation Score

In order to assess whether the coherence increase in cooperation is related to the team's performance, a correlation analysis was performed between coherence increase measures and cooperation scores. The correlation results for each cooperation task are shown in Figure 17 and Figure 18 with colored numbering to indicate the type of coherence increase measurement used for the computation. The results showed that there are both positive and negative correlations between game scores and coherence increase measures at specific regions. One notable positive correlation was found at Optode 10 during the initial reverse cooperation task when measured in all B, C, and D coherence increase measurement types. For type B, the first reverse cooperation task was found to be positively correlated with a correlation value of 0.7435. In addition to this finding, left DLPFC coherence was observed to have a positive correlation with game scores during the learned reverse cooperation task. For Optodes 1, 4, and 5, the correlation scores were observed as 0.497, 0.5089,and 0.5544, respectively.

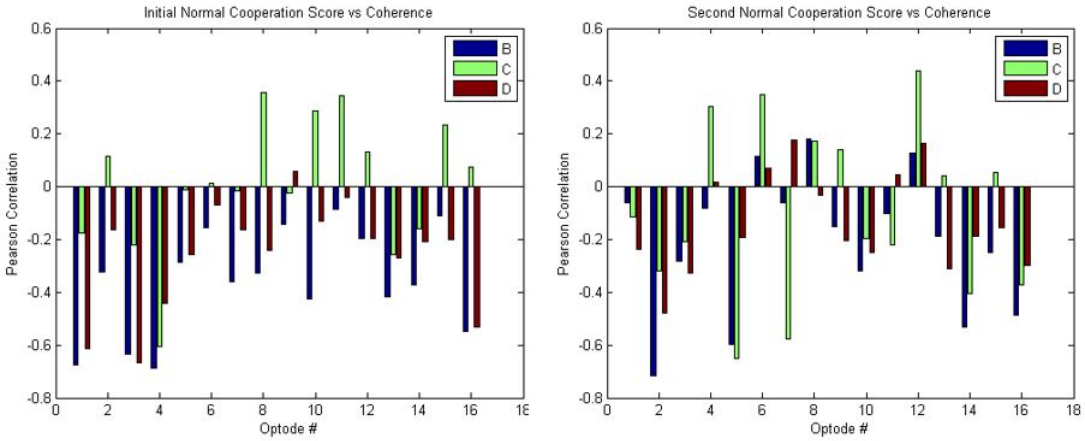


Figure 17: Pearson correlation results for the initial and second normal cooperation tasks vs. coherence increase

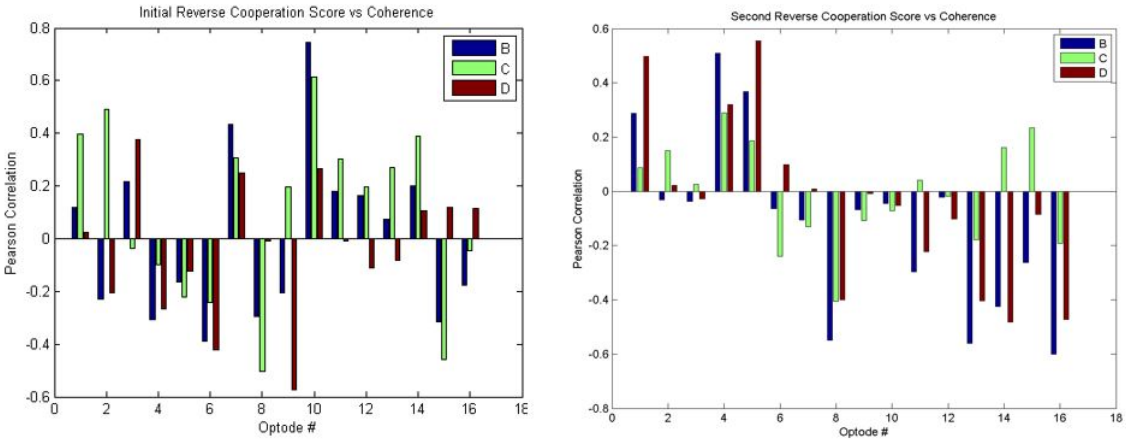


Figure 18: Pearson correlation results for the initial and second reverse cooperation tasks vs. coherence increase

4.2.3 Inter-brain Coherence Increase Across Optodes

In this study, functional connectivity across the measurable PFC regions is also investigated to observe whether activation in particular regions was associated with particular regions within PFC and whether co-activation patterns varied according to social task category. Functional connectivity across the measurable PFC regions is investigated by analyzing the inter-brain coherence increase across optodes for each task employing all coherence increase measurement methods. One-sample t-test calculations have been performed on only the eligible data for each optode within the optode pair belonging to a certain task. Significant IBC results are provided in Appendix C. FDR corrected results have been shown in Figure 19 and Table 9.

Table 9: Inter-brain coherence increase FDR corrected one-sample t-test results across optodes

Type	Opt #1	Opt #2	Social Task	T-statistic (df)	P-value	Effect size: r
B	15	16	Coop-Norm-II	t (5) = 12.6205	.007	.984
B	3	1	Coop-Rev-I	t (11) = 5.0943	.044	.838
C	2	9	Coop-Norm-I	t (11) = 4.2878	.032	.790
C	4	5	Coop-Norm-I	t (7) = 5.6263	.025	.904
C	4	9	Coop-Norm-I	t (8) = 6.2114	.016	.910
C	4	11	Coop-Norm-I	t (9) = 5.3898	.018	.873
C	12	1	Coop-Norm-I	t (8) = 7.5748	.008	.936

As illustrated in Table 9 and can be seen with the red line in Figure 19, the second cooperation normal task elicits significant coherence increase ($p < 0.01$) in the right DLPFC (between Optode 15 and 16) for Type B coherence increase measurement. This result is in line with the previous state-of-the art findings. On the other hand, as illustrated with the blue line, the reverse cooperation task is observed to elicit

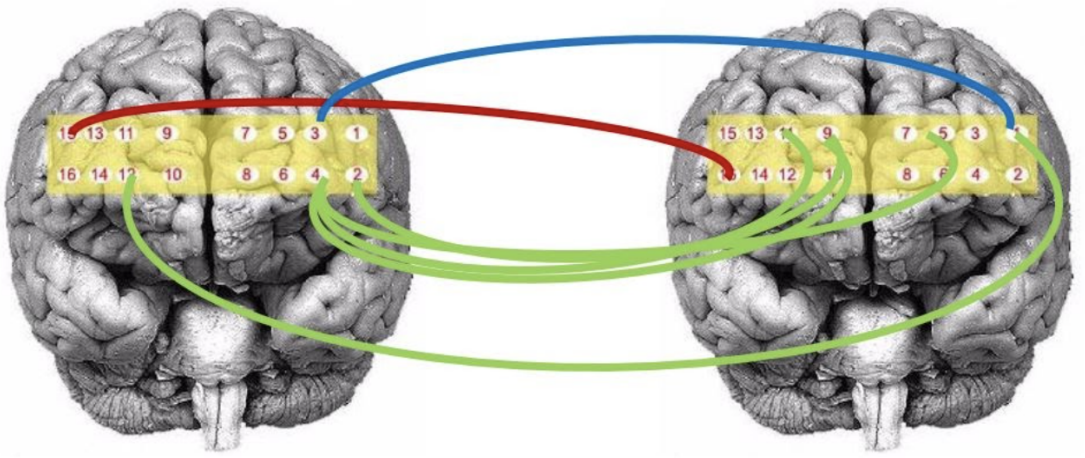


Figure 19: Inter-brain coherence increase results analyzed across optodes.
Red line: Cooperation Normal II task with Type B coherence increase measurement.
Blue line: Cooperation Reverse I task with Type B coherence increase measurement.
Green line: Cooperation Normal I task with Type C coherence increase measurement.

significant coherence increase ($p < 0.05$) in the left DLPFC (between Optode 1 and 3) for Type B coherence increase measurement showing lateralized coherence increase in the DLPFC for the cooperation tasks, depending on the regular or reverse version of the task.

In addition to Type B measurement results, Type C coherence difference measurement results shown with green lines reveal novel significant coherence increase ($p < 0.01$) between the left DLPFC and the Frontopolar Cortex, only in the cooperation-normal task. This result shows that the coherence of L-DLPFC and FC during social cooperation is significantly stronger than performing the task individually without socialization, which suggests the interworking of these two regions may be necessary for performing social tasks.

4.3 Attachment Style Effects

4.3.1 Activation Differences Between Secure and Insecure

In order to analyze the PFC activation differences between secure and insecure participants, mean HbO concentration changes were analyzed w.r.t. both baseline and rest periods. Analysis w.r.t. baseline measurement refers to changes in HbO concentration compared to the participants' mean HbO concentration levels in rest condition before the start of the experiment. Whereas, analysis w.r.t. rest period refers to changes in HbO concentration of participants compared to the levels measured during the rest period prior to the respective task. For both cases, two sample t-test was employed to compare the HbO responses of insecure and secure subject groups.

The results w.r.t. both baseline and prior rest period were depicted in Figure 20 and Figure 21 respectively and two sample t-test results were provided in Table 10. Only the initial tasks were analyzed w.r.t. baseline, whereas both the initial and second tasks were analyzed w.r.t. prior rest period.

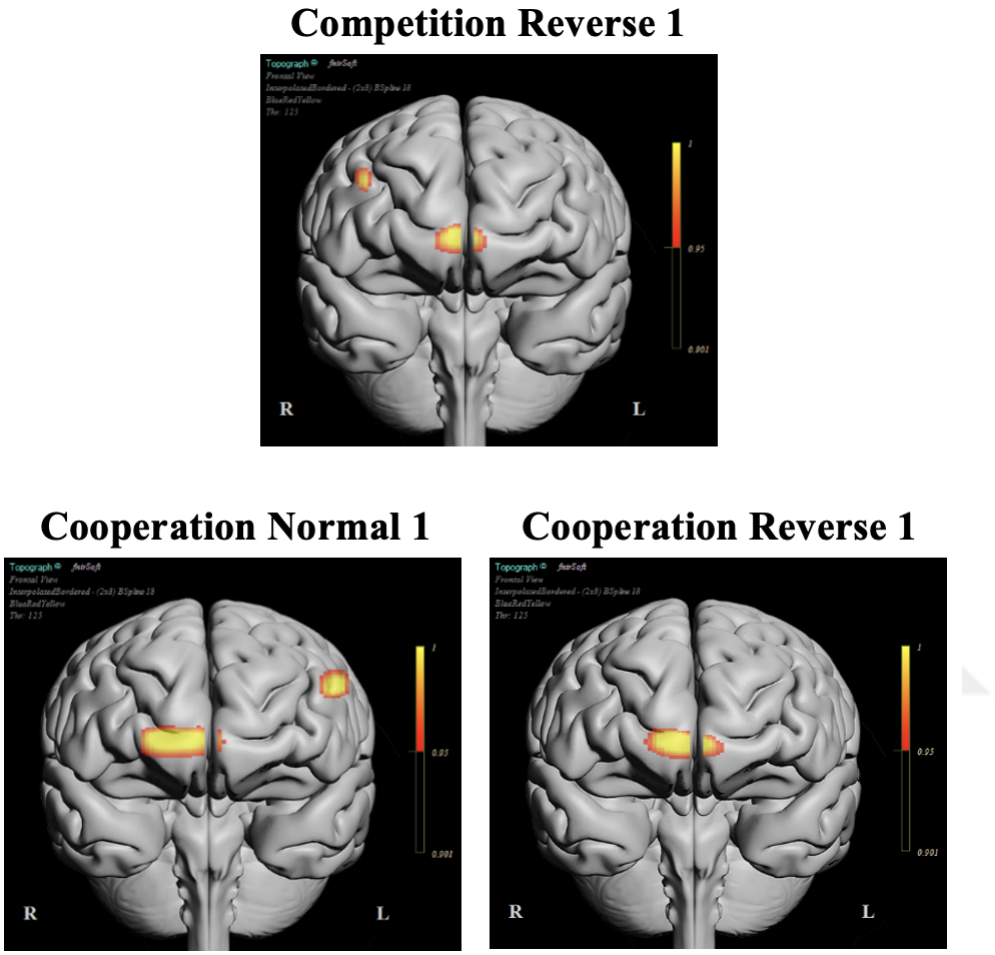


Figure 20: The PFC locations where significant mean HbO concentration change differences between secure and insecure subject groups were observed when analyzed w.r.t. baseline

According to activation values and t-test results, the major finding is that during competition as well as cooperation tasks, significant activation differences were observed between secure and insecure participants at the frontopolar cortex. More specifically, significant ($p<0.01$) right frontopolar (Optode 10) HbO activation differences were observed during initial cooperation tasks, along with significant activation differences at Optode 1 (left DLPFC) and Optode 12 (right DMPFC). In addition to the cooperation task results, significant activation differences at Optodes 8, 10, 12, and 13 were observed during the competition tasks, corresponding to the DMPFC and the right DLPFC regions.

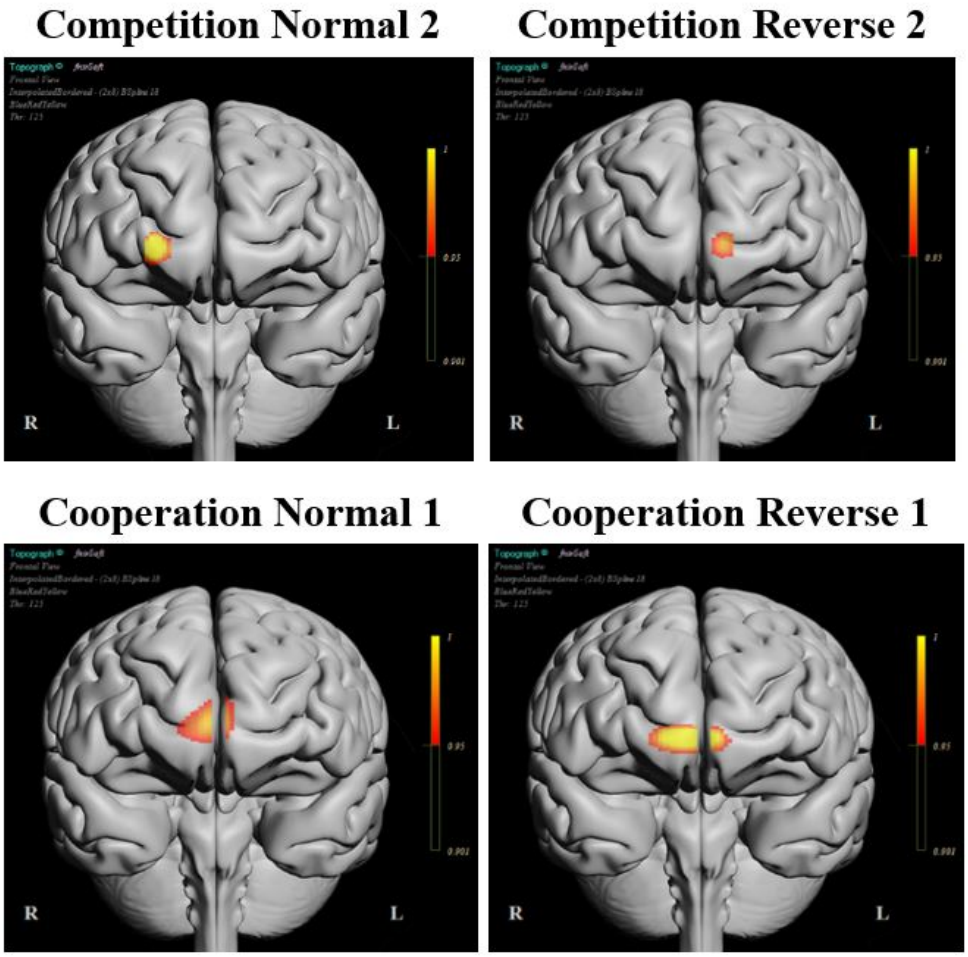


Figure 21: The PFC locations where significant mean HbO concentration change differences between secure and insecure subject groups were observed when analyzed w.r.t. prior rest period

Moreover, the frontopolar region of secure participants was observed to be activated, whereas the same region was deactivated in insecure participants. When the mean HbO concentration values of significant findings were analyzed, mean HbO concentration values of secure participants were observed to be higher and positive in general than the mean of insecure participants (Table 10).

Table 10: 2 sample t-test results showing significant attachment style differences in HbO concentration changes w.r.t. baseline (BL), and prior rest period (RST) and mean HbO concentration changes in secure and insecure participants. The optodes that have passed FDR correction are shown in bold font.

Optode #	Social Task	BL/RST	t(df)	p	r	Mean HbO Sec.	Mean HbO Ins.	Ax corr.
Opt 1	Coop-Norm-I	BL	t (34) = 2.1608	.038	.347	0.6613	0.0371	-0.027
Opt 8	Comp-Rev-II	RST	t (31) = 2.3385	.026	.387	-0.0049	-0.6400	-0.074
Opt 10	Comp-Rev-I	BL	t (28) = 2.1990	.036	.383	0.3219	-0.3947	-0.180
Opt 10	**Coop-Norm-I**	**BL**	**t (28) = 3.7784**	**.001**	**.581**	**0.5523**	**-0.4829**	**-0.155**
Opt 10	Coop-Norm-I	RST	t (28) = 2.3427	.026	.404	0.2746	-0.6221	-0.060
Opt 10	Coop-Rev-I	BL	t (27) = 2.6622	.012	.455	0.5439	-0.6137	-0.113
Opt 10	Coop-Rev-I	RST	t (27) = 2.0742	.048	.370	0.2646	-0.6620	0.004
Opt 12	Coop-Norm-I	BL	t (32) = 2.2701	.030	.372	0.5685	-0.0386	-0.046
Opt 12	Comp-Norm-II	RST	t (30) = 2.6687	.012	.438	0.1371	-0.7019	-0.270
Opt 13	Comp-Rev-I	BL	t (37) = 2.0277	.049	.316	0.2325	-0.2398	-0.186

4.3.2 Attachment Style Effects on Inter-brain Coherence

Attachment style effects have been investigated on inter-brain coherence values as well, despite the fact that the experiment was conducted with 8 pairs of secure – secure, 5 pairs of insecure – insecure and 11 pairs of secure – insecure participants. In order to understand whether attachment styles seem to affect inter-brain coherence during social interaction or not, differences regarding the coherence of pairs having both subjects classified with the same attachment styles and pairs with different attachment styles were investigated. For this purpose, secure – insecure and secure – secure participant groups' differences were selected as the focus of this analysis. Two sample t-tests were performed to compare these two groups of pairs. Those results with degrees of freedom 9 or more were considered and summarized in this subsection (see Table 11).

During the initial normal competition task, Optodes 2 ($p<0.05$) and 4 ($p<0.05$) located over the left DLPFC were identified as having significant inter-brain coherence differences between secure – secure and secure – insecure pairs, only across the Type D measurement. During the initial reverse competition task, Optode 14 ($p<0.05$) in Type B measurement and Optode 14 ($p<0.01$) in Type C measurement were identified as having significant inter-brain coherence difference between secure – secure and secure– insecure groups, which correspond to the right DLPFC. For the second (learned) normal competition task, only Optode 2 ($p<0.05$) in Type B measurement was identified as having significant inter-brain coherence difference, which corresponds to left DLPFC.

During the initial normal cooperation task, Optode 16 ($p<0.01$) in Type A was observed to show a solo task coherence increase difference between secure – secure and secure – insecure pairs. The solo tasks are independent of the task's nature; in other words, every solo task is identical to each other, independent from its period. Therefore, this result should be interpreted carefully. In addition to Type A finding, for the initial normal cooperation task Optode 1 ($p=0.01$) in Type C measurement was identified as having a significant inter-brain coherence difference between secure – secure and secure – insecure groups, which correspond to left DLPFC.

Table 11: 2 sample t-test results showing significant attachment style differences in inter-brain coherence analysis w.r.t. secure-insecure and secure-secure dyads

Optode #	Social Task	Type	T-statistic (df)	P-value	Effect size: r	Dyad having better IBS
Opt 1	Coop-Norm-I	C	t (9) = 3.2077	.010	.730	secure - insecure
Opt 2	Comp-Norm-I	D	t (10) = 2.5838	.027	.632	secure - insecure
Opt 2	Comp-Rev-II	B	t (9) = -2.6679	.025	.664	secure - secure
Opt 4	Comp-Norm-I	D	t (11) = 2.7702	.018	.641	secure - insecure
Opt 14	Comp-Rev-I	B	t (10) = -2.5086	.031	.621	secure - insecure
Opt 14	Comp-Rev-I	C	t (10) = -3.4254	.006	.734	secure - secure
Opt 16	Coop-Norm-I	A	t (10) = 3.1984	.009	.711	secure - insecure

CHAPTER 5

DISCUSSION, CONCLUSION AND FUTURE DIRECTIONS

5.1 Discussion and Conclusion

This study aims to contribute to a growing body of social cognition research by collecting hyperscanning data from various naturalistic social task conditions and utilizing intra-brain and inter-brain measures to explore the neural underpinnings of social engagement in reference to attachment tendencies. The study introduced three novel aspects to the study of social neuroscience. Firstly a naturalistic experimental procedure with a suitable control task is proposed to systematically isolate the effects of socialization. Secondly, a novel inter-brain coherence difference measurement methodology was proposed based on the structural properties of the designed experiment. Thirdly, the study focuses on assessing individual differences in reference to attachment theory to shed further light on the neural correlates of observed behavioral differences across various social conditions.

5.1.1 Activation Analysis Findings

In order to study social interaction in various social contexts, competitive and cooperative versions of the well-known Rock-Paper-Scissors (RPS) game were introduced. We believe that all four RPS tasks involve recruitment of executive capacities, such as attentional control, planning, monitoring, mentalizing, working memory, episodic retrieval and multitasking, which were previously linked with PFC functioning [60, 73, 77]. Our intra-brain activation analysis findings show significant increase in bilateral DLPFC activity during social tasks, signalling that the tasks utilized in this study creates a cognitive load in the PFC. The results for the first round of the regular cooperation task was the only task that passed the FDR correction, indicating that the initial regular cooperation task elicited the highest cognitive load compared to the reverse cooperation and competitive tasks.

The comparison of mean HbO increase levels during cooperative and competitive versions of the RPS game signals a need for more PFC activation in general during cooperation, which may be due to the novelty of the task compared to its well-known competitive version. However, since all measurable PFC regions showed higher levels of activation, and the unconventional competitive version of the RPS task (competition

reverse) did not affect this result, our results suggest that cooperation elicits a much greater and wider prefrontal activity compared to competition. In addition, for both the regular and reverse versions of the competitive and cooperative social tasks, bilateral DLPFC activation during the initial rounds was higher when compared to the follow-up rounds, which signals the need for DLPFC activation in coping with the novel social conditions. Moreover, although similar as well as distinct regions were found to be selectively associated with cooperation and competition in the current literature [80], the findings of this study suggest similarities in terms of the recruited PFC regions across these two contexts for this kind of social interaction. In addition, previous research also revealed employment of ToM regions during cooperation and competition [81, 82, 83, 84]. Although intra-brain analysis results of this study did not reveal such finding, inter-brain synchrony analysis results revealed significant frontopolar cortex mean coherence increase along with DLPFC during both competition and cooperation condition. This finding once again demonstrates the recruitment of ToM regions within PFC in cooperative and competitive social contexts and shows importance of inter-brain analysis of socially interacting individuals.

5.1.2 Inter-brain Coherence Analysis Findings

Compared to intra-brain analysis, which is useful to localize brain activations, inter-brain synchrony analysis promises revealing task-specific patterns during dynamic interaction of more than one person. By investigating correlation of neural activity from distinct interacting brains, additional layer of information is captured, which can provide insight in the study of social cognition [9]. This study adds further results to this line of research together with introduction of an experimental setup and inter-brain coherence increase measures. The main difference between this study and the related studies is that previous studies [9, 10, 11] predominantly employ simple computer-based competition and cooperation tasks where the participants try to perform mouse-clicking either simultaneously or as fast as possible. In contrast, this study employs more naturalistic competition and cooperation tasks via different forms of Rock-Paper-Scissors games, which were performed face to face almost as in a real-life social scenario. Moreover, the experimental procedure includes solo tasks in which the participants play the RPS game by themselves without seeing each other and without being subjected to any competitive or cooperative intents prior to each social task. Abovementioned existing studies assess inter-brain coherence comparing the mean coherence increase during social task with the mean coherence increase during prior rest period, which we have called Type B inter-brain coherence increase analysis in our study. The possibility of contrasting social and solo tasks (Type C) in this manner allowed us to isolate and explore the effects of socialization better, since it was the only difference introduced between a social task and a solo task.

Our inter-brain coherence analysis results with Type B and Type C measurement methods reveal significant inter-brain coherence increase in DLPFC, observed during both competition and cooperation tasks. Moreover, normal and reverse tasks showed significant coherence increase in different regions such that while normal competition and cooperation tasks were observed to elicit coherence increase in the right DLPFC,

reverse tasks were observed to elicit coherence increase in the left DLPFC. These findings are both in line with existing findings and partly contradictory as well. Existing studies such as [9] and [10] have shown that significant coherence in male/male dyads occurred only in either the right superior prefrontal cortex or right inferior prefrontal cortex during cooperation, but such effects were not observed during competition. In our case, we observed that both competition and cooperation tasks lead to a significant coherence increase in the right DLPFC. In addition, reverse competition and cooperation tasks were observed to elicit a significant coherence increase in the left DLPFC, which was not previously reported in the related literature. This may be due to the naturalistic setup of the experiment environment, which did not feature a computerized task like the ones used in previous studies, and the novelty of the social tasks presumably required more cognitive processing. Moreover, considering Type A solo coherence increase measurement findings, our results indicate bilateral DLPFC coherence increase due to the nature of the task itself. However, this type of coherence increase was observed only in one of the eight solo tasks, and the significance of coherence increase in DLPFC bilaterally was observed to be higher during the social tasks. Together with activation analysis findings, these results lead to the conclusion that social encounters improve bilateral DLPFC inter-brain coherence, thus utilized bilaterally depending on the nature and the novelty of the social task.

Despite the lack of a significant frontopolar cortex activation in our intra-brain analysis findings, a significant frontopolar cortex mean coherence increase was observed during both competition and cooperation conditions. This finding is best observed with the Type C measure, which was a novel coherence difference measurement method introduced in this thesis. The Type B measure also indicated a similar trend for the second normal cooperation task, where similar findings were reported in previous studies by [10], [25] and [27]. Moreover, analyzing inter-brain coherence across brain regions revealed a novel significant coherence increase between the left DLPFC and the Frontopolar Cortex during the regular cooperation task. This result shows that the coherence of L-DLPFC and FC during social cooperation is stronger than the coherence levels observed during solo performance without socialization, which suggests that the interworking of these two regions may be necessary for performing social tasks. FC has connectivity with both adjacent mid-ventrolateral prefrontal cortex (BA 47/12 and 45) and adjacent mid-dorsolateral prefrontal cortex (BA 9 and 46) [62]. Moreover, the lateral parts of FC were found to be co-activated with DLPFC showing engagement of FC and DLPFC in a meta-analysis study [79]. We think that the finding of IBC among FC and L-DLPFC observed in this study suggests task related interworking of these regions and shows that cooperation behavior should not only be related with right inferior/superior prefrontal region but needs further elaboration by experimenting with other forms of cooperative and social behavior.

In previous work a positive correlation on right superior PFC with the cooperation performance was reported [9, 10] however, no such strong finding has been observed in this study. Inter-brain coherence was observed to be slightly correlated with the reverse cooperation task performance in the left DLPFC and frontopolar cortex, which might be a lean conclusion to correlate coherence increase with task performance. This lack of finding for the association between inter-brain coherence and the performance

of cooperation in this study might be due to the complex nature of the cooperation task utilized. Thus, the results demonstrate that a generalized argument for the association between cooperation success and inter-brain coherence is not straight-forward.

5.1.3 Attachment Style Effects

According to the attachment theory [14, 31, 15], early experiences with the caregivers shape inter-personal functioning in adulthood [31, 34]. Disruptions in development of early secure attachment relationships are linked with general patterns of maladaptive functioning, which expresses importance of considering attachment theory in social cognition research as well as personality development and clinical psychology [103, 46]. A major goal for this study is to reveal differences in neural activity with respect to adult attachment orientation in regions of prefrontal cortex that contribute to social interaction. The intra-brain and inter-brain analysis findings that were summarized in previous subsections demonstrates the role of DLPFC and frontopolar cortex during social interaction. In this context, it is important to analyze whether these regions further exhibit differences with respect to adult attachment orientation.

Previous studies [20, 21, 18] have demonstrated the link between attachment-unrelated stress and attachment system activation. It was also observed that anxious-ambivalent adults signal chronic attachment system activation, and cognitive load on top of stress activates attachment-related worries in avoidant adults. The experimental setup realized in this study provides an environment in which the brain signals of stranger adult dyads are monitored while engaging in naturalistic social interaction. The social tasks performed were observed to elicit cognitive load and a motivation to win was tried to be created through monetary prizes which can contribute to distress throughout the experiment.

The analysis results of this study with respect to AT demonstrated differences in activation levels as well as in inter-brain synchrony with respect to attachment orientation in this kind of social context. One major finding in this study was observed through intra-brain activation analysis with respect to pre-dominant adult attachment orientation. Our findings reveal novel attachment style effects on BA10, namely the frontopolar cortex (FC). The results show that during both cooperation and competition tasks, the frontopolar cortex region of secure participants was activated, while on the contrary, the same region in insecure participants was deactivated. Moreover, a highly significant right frontopolar HbO activation difference was observed during the initial normal cooperation task, along with highly significant activation differences in the neighboring regions. These results suggest that there can be attachment style differences regarding prefrontal cortex activation during social interactions. This study, which employed 27 secure and 21 insecure (17 anxious, 2 avoidant, 2 disorganized) participants, clearly shows that during various forms of social interactions (competition and cooperation) frontopolar regions of secure participants elicit more activation compared to insecure participants. BA10 is active in a wide variety of cognitive tasks, including multitasking, working memory, mentalization [73], and also has a general role for exerting control for the direction of attention (stimulus-independent vs. stimulus-oriented information),

which is also referred as the “gateway hypothesis” [77].

This finding could be important due to the role of the frontopolar cortex have in social interaction. According to Fonagy & Luyten [46], an individual’s mentalizing capacity involves automatic (involving amygdala, VMPFC, basal ganglia, etc.) and controlled mentalizing mechanisms (involving MPFC, LPFC, rostral ACC, etc.). In times of stress, controlled mentalization is switched to automatic mentalization. During perceived stress, secure individuals seem to pursue controlled mentalizing longer, more effectively, and recover faster than insecure individuals [47]. In addition, secure mothers were observed to possess larger grey matter volume and higher activation in response to hearing baby cries in BA10, BA47 [49] and secure attachment style is linked with higher cortical activity on ToM related areas [53]. The finding that frontopolar regions of secure participants elicit more activation than insecure participants is in line with previous findings, which may be indicative of the employment of controlled mentalizing strategies in secure participants instead of switching to automatic mentalizing in novel complex social tasks. Moreover, Long et al. [22] argue that the human attachment system is comprised of an affective evaluation and a cognitive control network, the latter including MPFC. As a result of early relationships with the caregivers, different prototypical attachment pathways are formed specific to secure, avoidant and anxious attachment, leading to individual differences in social behaviour. Based on these views, the findings of this study may serve as a neurological marker for such behavioral differences, which needs further investigation.

Inter-brain coherence increase results were assessed as well to obtain a potential pointer whether there are attachment style differences regarding inter-brain coherence or not. Although dividing the dataset further into attachment-style groups lowered the number of data points used in this analysis, secure - insecure pairs were observed to have higher coherence increase values than secure - secure pairs in general. When we focus on the regions and the respective social tasks that had lead to significant IBS, only one finding stands out. L-DLPFC elicits significant inter-brain coherence increase difference between secure-secure and secure-insecure pairs during initial reverse competition task, and secure-secure pairs were observed to have better IBS in this region. However, the limitations due to the small sample size in the experiment and lack of further supporting IBS-attachment link finding in other areas that demonstrated IBS, make it difficult to make a strong claim about the link between attachment style differences and inter-brain coherence. While Reindl et al. [26] have reported higher brain-to-brain synchrony in the FPC during cooperation was associated with better emotion regulation of both parent and child, results from Miller et al. [27] did not reveal any strong evidence for links between inter-brain synchrony and attachment in mother-child dyads. Moreover, Nguyen et al. [29] has reported behavioral reciprocity in association with inter-brain coherence during cooperation which suggests a link between neural synchrony and parent-child interaction quality. Considering these evidence, further studies with a larger sample of attachment style pairings are required to elaborate on such findings.

In conclusion, our findings suggest that the frontopolar cortex, which is considered as a hub for metacognition, while contributing to social interaction, interestingly elicits activation differences with respect to adult attachment styles as well, with secure attachment orientation exhibiting stronger haemodynamic response, which may serve as a putative neuro-biologic marker underlying individual differences.

5.2 Future Directions

Neuroscience of social interactions and human attachment is still a quite recent field of investigation that needs further experimentation and understanding. Previous studies had typically observed individuals in isolation due to the rigid monitoring conditions of neuroimaging devices. This limitation has been overcome with certain devices such as fNIRS, EEG, and the hyperscanning methodology [5], where it is now possible to monitor brain processes in more than one people engaging in direct social interaction. The possibility of gaining real-time measurements of brain activity, such as PFC, while participants are engaged in the kinds of naturalistic tasks in everyday life opens up huge possibilities for cross-talk between neuroimaging and neuropsychology [61]. Initial social hyperscanning studies [9, 10] have been conducted based on computerized online interactions, which are different from people engaging in face-to-face reciprocal interaction as in real social encounters [2]. Thus, the value of findings from naturalistic social studies is indisputable, and such studies will be likely to develop our understanding of the underlying neural processes that shape our social behaviours. Therefore, future social neuroscience studies should be designed and conducted with the aim of discovering the particular brain areas and associated cognitive tasks that contribute to social behaviour.

This study aimed to provide various intra-brain and inter-brain findings embracing a second-person social neuroscience approach and to identify neuronal activity differences with respect to predominant attachment styles. However, it must be emphasized that there are several limitations to the study. The first limitation is regarding the neuroimaging modality used in the study. While fNIRS enables an easy to use imaging modality that can be deployed in a naturalistic environment, its spatial resolution is lower compared to techniques such as fMRI and PET. In addition, due to great variability in brain anatomy between individuals, specifying where an activation has occurred in the brain is both conceptually and technically more difficult than has been generally assumed in those techniques [104]. This causes uncertainty in localization, which in turn limits the effective resolution of functional imaging, especially for brain areas such as PFC that are involved in higher-order cognitive functions. Therefore, even though the inter-brain coherence results are in line with the previous studies, the exact anatomical locations of the channels should be interpreted with caution. In this study cross-optode, inter-brain coherence analysis was also performed, which may guide future studies for locating possible regions of interest for further analysis as in [10] and [27].

The second limitation of this study arises from experimenting with only male participants. This limitation mainly arised due to the necessity of a large forehead for proper placement of the sensor pad that belong to the neuroimaging devices utilized in the study. Previous studies [10, 27] have demonstrated differences in inter-brain synchrony when the sex composition of dyads are mixed. Since only male-male participant dyads are utilized, the findings of the study should not be generalized over entire population. Studies that both employ naturalistic social contexts and investigate with mixed dyad types are needed.

The third limitation of this study is the dependence of attachment style classification on questionnaires. There are a number of different methods to categorize adult attachment styles, and one of the methods is needed to be selected. Experiences in Close Relationship Scale (ECR) is a commonly used two-scale outcome questionnaire: however, since the experiment was conducted with Turkish participants, the Turkish translated version, which had already been validated in a scientific study, Sümer's ECR [43] was used. Therefore, considerations might arise regarding possible differences in findings using different measures of attachment in this kind of attachment theory research. As suggested by Long et al. [22], future studies may use more than one attachment measure in the same participant population to directly assess possible differences due to the attachment instruments employed.

Furthermore, studies directly associating inter-brain coherence with measures of attachment are needed [22]. Due to fewer participant pairs in this study and the existence of contradicting findings, no clear attachment style differences regarding inter-brain coherence were observed. However, few studies investigating parent-child inter-brain synchrony in social contexts have already been performed by [26], [27] and [29]. These studies are quite recent, and further studies investigating potential links between inter-brain coherence and other aspects of bio-behavioral synchrony are needed to understand potential neural synchrony implications, such as whether neural synchrony is beneficial or not for certain social contexts.

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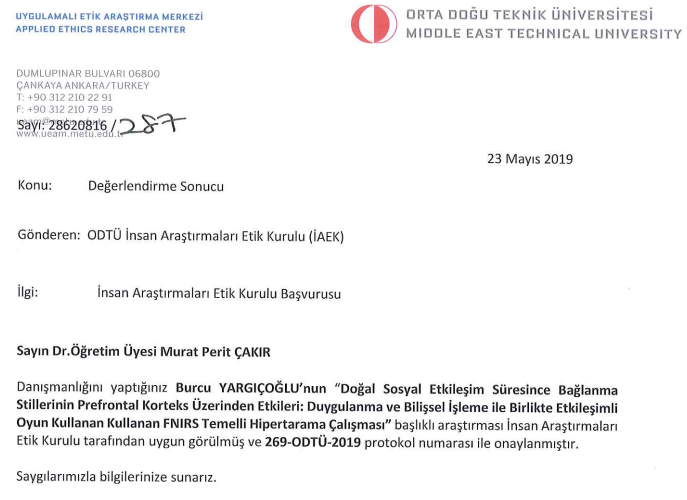
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APPENDIX A

M.E.T.U. ETHICS COMMITEE APPROVAL



UYGULAMALI ETİK ARAŞTIRMA MERKEZİ
APPLIED ETHICS RESEARCH CENTER

ORTA DOĞU TEKNİK ÜNİVERSİTESİ
MIDDLE EAST TECHNICAL UNIVERSITY

DUMLUPINAR BULVARI 06800
ÇANKAYA ANKARA/TURKEY
T: +90 312 210 22 91
F: +90 312 210 79 59
www.ueam.metu.edu.tr

Sayı: 28620816 / 287

23 Mayıs 2019

Konu: Değerlendirme Sonucu

Gönderen: ODTÜ İnsan Araştırmaları Etik Kurulu (İAEK)

İlgi: İnsan Araştırmaları Etik Kurulu Başvurusu

Sayın Dr.Öğretim Üyesi Murat Perit ÇAKIR

Danışmanlığını yaptığınız **Burcu YARGIÇOĞLU'nun "Doğal Sosyal Etkileşim Süresince Bağlanma Stillerinin Prefrontal Korteks Üzerinden Etkileri: Duygulanma ve Bilişsel İşleme ile Birlikte Etkileşimli Oyun Kullanan Kullanan FNIRS Temelli Hipertarama Çalışması"** başlıklı araştırması İnsan Araştırmaları Etik Kurulu tarafından uygun görülmüş ve **269-ODTÜ-2019** protokol numarası ile onaylanmıştır.

Saygılarımızla bilgilerinize sunarız.

Figure 22: M.E.T.U. Ethics Commitee Approval

APPENDIX B

QUESTIONNAIRES

B.1 Turkish Translation for Edinburgh Handedness Test

El Kullanım Testi

Lütfen aşağıdaki eylemler sırasında el kullanım tercihinizi ilgili sütuna bir artı işareti **(+)** koyarak belirtiniz. Eğer tercihiniz mecbur kalmadığınız sürece diğer elinizi kullanmayı asla tercih etmeyeceğiniz kadar güçlüyse ilgili sütuna iki artı işareti **(++)** yazınız. Eğer verilen eylem sırasında hangi elinizi kullandığınız sizin için hiçbir şekilde fark etmiyorsa iki sütuna da birer tane **+** işareti yazınız.

Aktivitelerin bazıları iki elin de kullanımını gerektirmektedir. Bu durumlarda el kullanımı ile ilgili koşul parantez içerisinde belirtilmiştir. Lütfen tüm soruları yanıtlamaya çalışın ve yalnızca ilgili aktivite veya nesne ile ilgili hiçbir deneyiminiz yoksa soruyu boş bırakın.

		SOL	**SAĞ**
1	Yazı yazmak		
2	Resim çizmek		
3	Bir cismi fırlatmak		
4	Makas kullanmak		
5	Diş fırçalamak		
6	Bıçak kullanmak (çatal olmadan)		
7	Kaşık kullanmak		
8	Süpürge kullanmak (üstteki el)		
9	Kibrit yakmak (kibriti tutan el)		
10	Kutu, kavanoz açmak (kapağı tutan el)		
i	Tekme atmak için (ör. topa vurmak) hangi ayağınızı tercih edersiniz?		
ii	Tek gözünüzü kullanmanız gerektiğinde (ör. nişan almak) hangisini tercih edersiniz?		

Figure 23: Turkish translation for Edinburgh handedness test

B.2 Turkish Experiences in Close Relationships Scale (YİYE)



Aşağıdaki maddeler romantik ilişkilerinizde hissettiğiniz duygularla ilintilidir. Bu araştırmada sizin ilişkinizde yalnızca şu anda değil genel olarak neler olduğuyla ya da neler yaşadığınızla ilgilenmekteyiz. Maddelerde sözü geçen "birlikte olduğum kişi" ifadesi ile romantik ilişkide bulunduğunuz kişi kastedilmektedir. Eğer halihazırda bir romantik ilişki içerisinde değilseniz, aşağıdaki maddeleri bir ilişki içinde olduğunuzu varsayarak cevaplandırınız. Lütfen her bir maddenin ilişkilerinizdeki duygu ve düşüncelerinizi ne oranda yansıttığını karşılarındaki 7 aralıklı ölçek üzerinde, ilgili rakam üzerine çarpı (**X**) koyarak gösteriniz.

	Hiç katılmıyorum			*Kararsızım / fikrim yok*			*Tamamen katılıyorum*
	1	2	3	4	5	6	7
1. Gerçekte ne hissettiğimi birlikte olduğum kişiye göstermemeyi tercih ederim.							
2. Terk edilmekten korkarım.							
3. Romantik ilişkide olduğum kişilere yakın olmak konusunda çok rahatım.							
4. İlişkilerim konusunda çok kaygılıyım.							
5. Birlikte olduğum kişi bana yakınlaşmaya başlar başlamaz kendimi geri çekiyorum.							
6. Romantik ilişkide olduğum kişilerin beni, benim onları umursadığım kadar umursamayacaklarından endişelenirim.							
7. Romantik ilişkide olduğum kişi çok yakın olmak istediğinde rahatsızlık duyarım.							
8. Birlikte olduğum kişiyi kaybedeceğim diye çok kaygılanırım.							
9. Birlikte olduğum kişilere açılma konusunda kendimi rahat hissetmem.							
10. Genellikle, birlikte olduğum kişinin benim için hissettiklerinin benim onun için hissettiklerim kadar güçlü olmasını arzu ederim.							
	1	2	3	4	5	6	7
11. Birlikte olduğum kişiye yakın olmayı isterim, ama sürekli kendimi geri çekerim.							
12. Genellikle birlikte olduğum kişiyle tamamen bütünleşmek isterim ve bu bazen onları korkutup benden uzaklaştırır.							
13. Birlikte olduğum kişilerin benimle çok yakınlaşması beni gerginleştirir.							
14. Yalnız kalmaktan endişelenirim.							
15. Özel duygu ve düşüncelerimi birlikte olduğum kişiyle paylaşmak konusunda oldukça rahatımdır.							
16. Çok yakın olma arzum bazen insanları korkutup uzaklaştırır.							
17. Birlikte olduğum kişiyle çok yakınlaşmaktan kaçınmaya çalışırım.							
18. Birlikte olduğum kişi tarafından sevildiğimin sürekli ifade edilmesine gereksinim duyarım.							
19. Birlikte olduğum kişiyle kolaylıkla yakınlaşabilirim.							
20. Birlikte olduğum kişileri bazen daha fazla duygu ve bağlılık göstermeleri için zorladığımı hissederim.							
	1	2	3	4	5	6	7
21. Birlikte olduğum kişilere güvenip dayanma konusunda kendimi rahat bırakmakta zorlanırım.							
22. Terk edilmekten pek korkmam.							
23. Birlikte olduğum kişilere fazla yakın olmamayı tercih ederim.							
24. Birlikte olduğum kişinin bana ilgi göstermesini sağlayamazsam üzülür ya da kızarım.							
25. Birlikte olduğum kişiye hemen hemen herşeyi anlatırım.							
26. Birlikte olduğum kişinin bana istediğim kadar yakın olmadığını düşünürüm.							
27. Sorunlarımı ve kaygılarımı genellikle birlikte olduğum kişiyle tartışırım.							
28. Bir ilişkide olmadığım zaman kendimi biraz kaygılı ve güvensiz hissederim.							
29. Birlikte olduğum kişilere güvenip dayanmakta rahatımdır.							
30. Birlikte olduğum kişi istediğim kadar yakınımda olmadığında kendimi engellenmiş hissederim.							
	1	2	3	4	5	6	7
31. Birlikte olduğum kişilerden teselli, öğüt ya da yardım istemekten rahatsız olmam.							
32. İhtiyaç duyduğumda birlikte olduğum kişiye ulaşamazsam kendimi engellenmiş hissederim.							
33. İhtiyaç duyduğumda birlikte olduğum kişiden yardım istemek işe yarar.							
34. Birlikte olduğum kişiler beni onaylamadıkları zaman kendimi gerçekten kötü hissederim.							
35. Rahatlama ve güvencenin yanısıra birçok şey için birlikte olduğum kişiyi ararım.							
36. Birlikte olduğum kişi benden ayrı zaman geçirdiğinde üzülürüm.							

Figure 24: Turkish Experiences in Close Relationships Scale (YİYE)

APPENDIX C

SIGNIFICANT IBC INCREASE RESULTS ACROSS OPTODES WITHOUT FDR CORRECTION

Table 12: Significant Type A inter-brain coherence increase one-sample t-test results across optodes for competition normal tasks

Type	Social Task	opt #1	opt #2	p	df	tstat
A	Comp-Norm-I	1	10	0,03987331	5	2,19347563
A	Comp-Norm-I	11	9	0,03168646	12	2,04550110
A	Comp-Norm-II	2	2	0,03924543	13	1,90966605
A	Comp-Norm-II	2	16	0,02697613	12	2,13623268
A	Comp-Norm-II	3	1	0,03236633	10	2,07505483
A	Comp-Norm-II	4	1	0,02519404	7	2,35936843
A	Comp-Norm-II	4	2	0,01672639	8	2,56372003
A	Comp-Norm-II	7	4	0,00860161	4	3,92306331
A	Comp-Norm-II	7	6	0,00600478	5	3,84930914
A	Comp-Norm-II	8	5	0,00743235	5	3,64248766
A	Comp-Norm-II	8	11	0,02426517	7	2,38491282
A	Comp-Norm-II	9	5	0,00885994	8	2,97556758
A	Comp-Norm-II	11	2	0,03898050	10	1,96366074
A	Comp-Norm-II	11	14	0,03389335	9	2,07523459
A	Comp-Norm-II	11	16	0,01744947	11	2,40537624
A	Comp-Norm-II	13	5	0,04060442	7	2,03584890
A	Comp-Norm-II	13	11	0,04712426	10	1,84868207
A	Comp-Norm-II	13	12	0,04547811	7	1,95898052
A	Comp-Norm-II	13	14	0,03330349	9	2,08606546
A	Comp-Norm-II	13	15	0,00192919	6	4,55816568
A	Comp-Norm-II	14	11	0,03119362	9	2,12638234
A	Comp-Norm-II	16	11	0,00937500	11	2,75417961
A	Comp-Norm-II	16	13	0,02820447	9	2,18827165
A	Comp-Norm-II	16	14	0,02506986	9	2,26044993
A	Comp-Norm-II	16	16	0,01955442	13	2,29376075

Table 13: Significant Type A inter-brain coherence increase one-sample t-test results across optodes for competition reverse tasks

Type	Social Task	opt #1	opt #2	p	df	tstat
A	Comp-Rev-I	1	13	0,03895373	11	1,94401490
A	Comp-Rev-II	1	3	0,00254356	10	3,57101742
A	Comp-Rev-II	1	5	0,02254253	7	2,43505210
A	Comp-Rev-II	1	6	0,00880604	5	3,48246736
A	Comp-Rev-II	7	15	0,00814397	5	3,55574213
A	Comp-Rev-II	7	16	0,04008581	8	2,00276858
A	Comp-Rev-II	15	7	0,04538257	5	2,09116808

Table 14: Significant Type A inter-brain coherence increase one-sample t-test results across optodes for cooperation normal tasks

Type	Social Task	opt #1	opt #2	p	df	tstat
A	Coop-Norm-I	10	5	0,03119328	4	2,56380072
A	Coop-Norm-I	10	6	0,03230702	7	2,19067827
A	Coop-Norm-I	14	8	0,03473395	8	2,09507262
A	Coop-Norm-I	16	8	0,01256535	8	2,74814922
A	Coop-Norm-I	16	12	0,00859137	9	2,91457825
A	Coop-Norm-II	15	1	0,04977984	6	1,94636322

Table 15: Significant Type A inter-brain coherence increase one-sample t-test results across optodes for cooperation reverse tasks

Type	Social Task	opt #1	opt #2	p	df	tstat
A	Coop-Rev-II	6	5	0,03454093	3	2,77841539
A	Coop-Rev-II	12	5	0,03644386	4	2,41841731

Table 16: Significant Type B inter-brain coherence increase one-sample t-test results across optodes for competition normal tasks

Type	Social Task	opt #1	opt #2	p	df	tstat
B	Comp-Norm-I	1	12	0,00470904	8	3,39585063
B	Comp-Norm-I	1	16	0,04031291	10	1,94339785
B	Comp-Norm-I	2	1	0,04924463	8	1,86945633
B	Comp-Norm-I	2	8	0,02394987	7	2,39381154
B	Comp-Norm-I	2	16	0,02985472	13	2,06272615
B	Comp-Norm-I	3	14	0,04348725	11	1,87906117
B	Comp-Norm-I	3	15	0,04301911	9	1,92734272

Table 17: Significant Type B inter-brain coherence increase one-sample t-test results across optodes for competition reverse tasks

Type	Social Task	opt #1	opt #2	p	df	tstat
B	Comp-Rev-II	2	2	0,04545876	13	1,82587860
B	Comp-Rev-II	2	5	0,04707118	6	1,98672498
B	Comp-Rev-II	2	10	0,01104441	7	2,92794370
B	Comp-Rev-II	9	10	0,04605501	6	2,00247397
B	Comp-Rev-II	14	10	0,03117578	5	2,39046823

Table 18: Significant Type B inter-brain coherence increase one-sample t-test results across optodes for cooperation normal tasks

Type	Social Task	opt #1	opt #2	p	df	tstat
B	Coop-Norm-I	1	5	0,04478708	9	1,90218779
B	Coop-Norm-I	2	9	0,01344423	11	2,55222291
B	Coop-Norm-I	2	11	0,00919961	11	2,76474109
B	Coop-Norm-I	2	16	0,04555650	13	1,82464525
B	Coop-Norm-I	4	9	0,01598516	8	2,59286668
B	Coop-Norm-I	4	11	0,01000790	9	2,82095402
B	Coop-Norm-I	12	15	0,01288661	5	3,13631370
B	Coop-Norm-II	2	8	0,01436772	6	2,86175811
B	Coop-Norm-II	2	11	0,01600351	9	2,53433282
B	Coop-Norm-II	5	15	0,03699713	5	2,25304099
B	Coop-Norm-II	5	16	0,04743854	6	1,98111581
B	Coop-Norm-II	8	9	0,01292390	5	3,13375187
B	Coop-Norm-II	8	11	0,01560707	6	2,79877894
B	Coop-Norm-II	8	15	0,04067619	4	2,31758034
B	Coop-Norm-II	8	16	0,00230464	7	4,09372875
B	Coop-Norm-II	10	9	0,01916948	5	2,79233562
B	Coop-Norm-II	10	11	0,03843480	5	2,22267205
B	Coop-Norm-II	10	16	0,03791186	7	2,08233117
B	Coop-Norm-II	11	9	0,01192944	10	2,66098595
B	Coop-Norm-II	11	11	0,03178991	12	2,04365349
B	Coop-Norm-II	11	12	0,02569917	5	2,54788175
B	Coop-Norm-II	11	13	0,02688604	9	2,21762489
B	Coop-Norm-II	11	15	0,04354105	7	1,98851199
B	Coop-Norm-II	11	16	0,04899207	10	1,82493253
B	Coop-Norm-II	12	9	0,02782122	6	2,36839545
B	Coop-Norm-II	12	11	0,02025808	5	2,74570972
B	Coop-Norm-II	13	9	0,03079624	8	2,17235056
B	Coop-Norm-II	13	16	0,02809348	8	2,23125391
B	Coop-Norm-II	14	7	0,00964434	6	3,17123108
B	Coop-Norm-II	14	9	0,02081591	7	2,48942128
B	Coop-Norm-II	15	9	0,00253286	5	4,75859976
B	Coop-Norm-II	15	16	0,00002774	5	12,62054345
B	Coop-Norm-II	16	7	0,00387951	7	3,68976308
B	Coop-Norm-II	16	9	0,00807930	9	2,95236933
B	Coop-Norm-II	16	11	0,04283527	10	1,90669808
B	Coop-Norm-II	16	16	0,04515262	12	1,84204115

Table 19: Significant Type B inter-brain coherence increase one-sample t-test results across optodes for cooperation reverse tasks

Type	Social Task	opt #1	opt #2	p	df	tstat
B	Coop-Rev-I	1	1	0,03676149	13	1,94657611
B	Coop-Rev-I	1	5	0,04647087	9	1,87908632
B	Coop-Rev-I	2	2	0,02097169	13	2,25595753
B	Coop-Rev-I	2	4	0,00826685	10	2,87474670
B	Coop-Rev-I	2	5	0,00887115	7	3,08292702
B	Coop-Rev-I	3	1	0,00017354	11	5,09438894
B	Coop-Rev-I	3	2	0,00263966	8	3,79430634
B	Coop-Rev-I	3	3	0,00666036	14	2,83175003
B	Coop-Rev-I	3	4	0,00258894	11	3,47676382
B	Coop-Rev-I	3	5	0,00930909	7	3,04866584
B	Coop-Rev-I	3	6	0,02568798	8	2,28861310
B	Coop-Rev-I	3	7	0,00118844	7	4,63739407
B	Coop-Rev-I	3	10	0,00045216	4	8,83918634
B	Coop-Rev-I	3	11	0,01077458	9	2,77577315
B	Coop-Rev-I	3	13	0,04578715	11	1,84846084
B	Coop-Rev-I	4	2	0,04673812	10	1,85370012
B	Coop-Rev-I	5	4	0,01347684	7	2,78882919
B	Coop-Rev-I	5	8	0,04707645	5	2,06233647
B	Coop-Rev-I	6	4	0,04660610	11	1,83790403
B	Coop-Rev-I	7	3	0,02634446	7	2,32903247
B	Coop-Rev-I	7	4	0,00073394	6	5,53387943
B	Coop-Rev-I	7	6	0,01498897	7	2,71508169
B	Coop-Rev-I	7	8	0,01346942	3	4,05984180
B	Coop-Rev-I	9	6	0,01686236	8	2,55851668
B	Coop-Rev-I	9	8	0,04117276	5	2,16804994
B	Coop-Rev-I	9	15	0,02783392	6	2,36806134
B	Coop-Rev-I	10	13	0,02888246	5	2,45241053
B	Coop-Rev-II	3	1	0,01627116	9	2,52422402

Table 20: Significant Type C inter-brain coherence increase one-sample t-test results across optodes for competition normal tasks

Type	Social Task	opt #1	opt #2	p	df	tstat
C	Comp-Norm-I	1	8	0,04779349	6	1,97573759
C	Comp-Norm-I	1	9	0,03211024	8	2,14553412
C	Comp-Norm-I	2	3	0,01905870	9	2,42783929
C	Comp-Norm-I	2	7	0,02897974	8	2,21134308
C	Comp-Norm-I	2	8	0,00087808	7	4,89848202
C	Comp-Norm-I	2	9	0,04973989	11	1,79901179
C	Comp-Norm-I	2	11	0,01891280	11	2,35982428
C	Comp-Norm-I	2	12	0,02080510	8	2,42368466
C	Comp-Norm-I	2	13	0,00466378	9	3,29340243
C	Comp-Norm-I	2	14	0,00420283	11	3,20326592
C	Comp-Norm-I	2	16	0,00441656	13	3,07676346
C	Comp-Norm-I	3	11	0,02230008	10	2,29542520
C	Comp-Norm-I	3	13	0,01841767	12	2,34816404
C	Comp-Norm-I	3	14	0,02678581	11	2,16142071
C	Comp-Norm-I	4	8	0,02505188	7	2,36321490
C	Comp-Norm-I	4	11	0,04481731	9	1,90176589
C	Comp-Norm-I	4	14	0,02107496	12	2,27377152
C	Comp-Norm-I	5	9	0,00592863	9	3,14369537
C	Comp-Norm-I	5	11	0,01169480	10	2,67255851
C	Comp-Norm-I	5	13	0,02399162	8	2,33237787
C	Comp-Norm-I	5	16	0,04724372	8	1,89641973
C	Comp-Norm-I	7	9	0,00284797	9	3,60586377
C	Comp-Norm-I	7	11	0,03295808	10	2,06424940
C	Comp-Norm-I	9	9	0,00403854	14	3,08451009
C	Comp-Norm-I	9	11	0,02379143	12	2,20644907
C	Comp-Norm-I	11	5	0,03632029	10	2,00614158
C	Comp-Norm-I	11	7	0,01468918	10	2,53969814
C	Comp-Norm-I	11	9	0,00933317	12	2,71830309
C	Comp-Norm-I	11	11	0,01710024	14	2,34635022
C	Comp-Norm-I	11	13	0,03205135	11	2,05784883
C	Comp-Norm-I	14	5	0,02640587	9	2,22866540
C	Comp-Norm-I	14	7	0,02502066	8	2,30547498
C	Comp-Norm-I	14	14	0,00597226	15	2,85909980
C	Comp-Norm-I	16	7	0,01599584	9	2,53462512
C	Comp-Norm-I	16	14	0,01096467	12	2,63114375
C	Comp-Norm-II	2	5	0,01477667	6	2,84035072
C	Comp-Norm-II	2	10	0,02940239	7	2,25451954

Table 21: Significant Type C inter-brain coherence increase one-sample t-test results across optodes for competition reverse tasks

Type	Social Task	opt #1	opt #2	p	df	tstat
C	Comp-Rev-I	2	3	0,01568587	9	2,54655142
C	Comp-Rev-II	1	2	0,01818053	6	2,68360508
C	Comp-Rev-II	1	7	0,03173773	6	2,27220281
C	Comp-Rev-II	2	2	0,00134113	13	3,69760592
C	Comp-Rev-II	2	8	0,01640290	7	2,65284806
C	Comp-Rev-II	2	12	0,01314259	7	2,80630179
C	Comp-Rev-II	2	13	0,01819641	8	2,50961377
C	Comp-Rev-II	2	16	0,03811790	12	1,94006209
C	Comp-Rev-II	6	6	0,02135960	10	2,32073554
C	Comp-Rev-II	6	9	0,04532950	7	1,96120200
C	Comp-Rev-II	8	6	0,04294949	6	2,05287900
C	Comp-Rev-II	13	5	0,04081019	7	2,03242339
C	Comp-Rev-II	14	1	0,03227963	8	2,14215603
C	Comp-Rev-II	15	1	0,03003159	7	2,24016588
C	Comp-Rev-II	15	3	0,03025225	7	2,23520387
C	Comp-Rev-II	16	1	0,04797818	7	1,92263908
C	Comp-Rev-II	16	12	0,00437831	7	3,59855822

Table 22: Significant Type C inter-brain coherence increase one-sample t-test results across optodes for cooperation normal I task

Type	Social Task	opt #1	opt #2	p	df	tstat
C	Coop-Norm-I	1	5	0,04210329	9	1,94075986
C	Coop-Norm-I	1	9	0,02959547	8	2,19786173
C	Coop-Norm-I	1	13	0,03458607	11	2,01359875
C	Coop-Norm-I	1	16	0,00414441	10	3,28000838
C	Coop-Norm-I	2	1	0,01881170	8	2,48827233
C	Coop-Norm-I	2	4	0,02969332	11	2,10207433
C	Coop-Norm-I	2	6	0,03339271	12	2,01572136
C	Coop-Norm-I	2	8	0,01671080	7	2,64003875
C	Coop-Norm-I	2	9	0,00064085	11	4,28788135
C	Coop-Norm-I	2	16	0,03547538	13	1,96659125
C	Coop-Norm-I	3	5	0,03371059	7	2,16187351
C	Coop-Norm-I	3	8	0,02942669	7	2,25395960
C	Coop-Norm-I	3	9	0,01403478	9	2,61435538
C	Coop-Norm-I	4	1	0,04621316	11	1,84294791
C	Coop-Norm-I	4	3	0,00873244	12	2,75423010
C	Coop-Norm-I	4	5	0,00039692	7	5,62630582
C	Coop-Norm-I	4	6	0,00782777	12	2,81322299
C	Coop-Norm-I	4	7	0,00913829	6	3,21391881
C	Coop-Norm-I	4	9	0,00012811	8	6,21144610
C	Coop-Norm-I	4	11	0,00021940	9	5,38984133
C	Coop-Norm-I	4	13	0,01822777	9	2,45501534
C	Coop-Norm-I	4	16	0,01494648	11	2,49267545
C	Coop-Norm-I	5	1	0,02118895	9	2,36320970
C	Coop-Norm-I	5	7	0,02145123	8	2,40408364
C	Coop-Norm-I	5	9	0,00329867	9	3,51204974
C	Coop-Norm-I	6	3	0,02317390	9	2,30853107
C	Coop-Norm-I	6	9	0,00980060	9	2,83377685
C	Coop-Norm-I	6	15	0,04745746	7	1,93005306
C	Coop-Norm-I	7	5	0,02591717	8	2,28292250
C	Coop-Norm-I	7	7	0,02353406	10	2,26374522
C	Coop-Norm-I	7	9	0,02197658	9	2,34093161
C	Coop-Norm-I	8	1	0,02740736	6	2,37937669
C	Coop-Norm-I	8	9	0,04648817	6	1,99571814
C	Coop-Norm-I	10	9	0,02870919	6	2,34539994
C	Coop-Norm-I	12	1	0,00003228	8	7,57489555
C	Coop-Norm-I	12	4	0,04100408	8	1,98814534
C	Coop-Norm-I	12	9	0,04441494	8	1,93646448
C	Coop-Norm-I	12	14	0,04268208	8	1,96222305
C	Coop-Norm-I	12	15	0,00408678	5	4,23949457
C	Coop-Norm-I	14	1	0,00981165	11	2,72871694
C	Coop-Norm-I	14	5	0,02573132	9	2,24451136
C	Coop-Norm-I	14	9	0,00508225	10	3,15966979
C	Coop-Norm-I	14	11	0,00263443	11	3,46688017
C	Coop-Norm-I	14	15	0,02484624	9	2,26593152
C	Coop-Norm-I	15	1	0,03816297	10	1,97641789
C	Coop-Norm-I	16	1	0,00348599	10	3,38260605
C	Coop-Norm-I	16	16	0,03384105	15	1,96924871

Table 23: Significant Type C inter-brain coherence increase one-sample t-test results across optodes for cooperation normal II task

Type	Social Task	opt #1	opt #2	p	df	tstat
C	Coop-Norm-II	1	9	0,04248600	5	2,14320584
C	Coop-Norm-II	2	7	0,00350181	6	4,01435539
C	Coop-Norm-II	2	11	0,02784807	9	2,19607234
C	Coop-Norm-II	4	7	0,03781348	3	2,67098432
C	Coop-Norm-II	6	7	0,04925257	4	2,14525184
C	Coop-Norm-II	6	11	0,02307451	6	2,50605019
C	Coop-Norm-II	6	15	0,01608387	3	3,79252409
C	Coop-Norm-II	6	16	0,04468873	7	1,97086285
C	Coop-Norm-II	7	4	0,02807810	3	3,03347747
C	Coop-Norm-II	8	9	0,02119840	5	2,70761316
C	Coop-Norm-II	8	15	0,01974535	4	3,01153340
C	Coop-Norm-II	8	16	0,02498693	7	2,36497976
C	Coop-Norm-II	9	9	0,01650434	12	2,40840525
C	Coop-Norm-II	9	15	0,00893992	5	3,46841209
C	Coop-Norm-II	10	8	0,03786519	6	2,14400546
C	Coop-Norm-II	10	9	0,03319304	5	2,33992851
C	Coop-Norm-II	10	11	0,02559499	5	2,55122106
C	Coop-Norm-II	10	15	0,02151092	3	3,38218865
C	Coop-Norm-II	10	16	0,03505482	7	2,13539300
C	Coop-Norm-II	11	9	0,00370434	10	3,34651741
C	Coop-Norm-II	11	11	0,00928732	12	2,72096345
C	Coop-Norm-II	11	12	0,02488197	5	2,57448245
C	Coop-Norm-II	11	13	0,04978172	9	1,83586698
C	Coop-Norm-II	11	15	0,01146965	7	2,90142390
C	Coop-Norm-II	11	16	0,02704265	10	2,18174952
C	Coop-Norm-II	12	7	0,03666684	4	2,41278046
C	Coop-Norm-II	12	9	0,04075731	6	2,09074161
C	Coop-Norm-II	12	11	0,04230128	5	2,14665085
C	Coop-Norm-II	13	9	0,02381712	8	2,33705424
C	Coop-Norm-II	14	9	0,04726112	7	1,93286909
C	Coop-Norm-II	14	15	0,02606827	5	2,53616886
C	Coop-Norm-II	15	9	0,00836594	5	3,53044264
C	Coop-Norm-II	15	15	0,03696173	7	2,09952100
C	Coop-Norm-II	15	16	0,01122485	5	3,25983814
C	Coop-Norm-II	16	2	0,03984294	11	1,93074261
C	Coop-Norm-II	16	7	0,01484063	7	2,72196381
C	Coop-Norm-II	16	9	0,02279116	9	2,31870534

Table 24: Significant Type C inter-brain coherence increase one-sample t-test results across optodes for cooperation reverse I task

Type	Social Task	opt #1	opt #2	p	df	tstat
C	Coop-Rev-I	1	2	0,03753025	7	2,08918315
C	Coop-Rev-I	1	5	0,01254453	9	2,68284027
C	Coop-Rev-I	1	7	0,02733596	7	2,30395047
C	Coop-Rev-I	1	10	0,03537997	4	2,44586201
C	Coop-Rev-I	2	4	0,02567966	10	2,21231036
C	Coop-Rev-I	2	7	0,04015227	8	2,00169931
C	Coop-Rev-I	3	1	0,00084428	11	4,12422561
C	Coop-Rev-I	3	2	0,00093218	8	4,55407478
C	Coop-Rev-I	3	3	0,01362227	14	2,46502004
C	Coop-Rev-I	3	4	0,01053486	11	2,68892107
C	Coop-Rev-I	3	5	0,00155128	7	4,41431389
C	Coop-Rev-I	3	6	0,01741231	8	2,53789685
C	Coop-Rev-I	3	7	0,00203603	7	4,19275771
C	Coop-Rev-I	3	10	0,00039844	4	9,13499339
C	Coop-Rev-I	3	11	0,04221186	9	1,93915490
C	Coop-Rev-I	4	2	0,04743493	10	1,84467223
C	Coop-Rev-I	4	5	0,02874683	7	2,26980922
C	Coop-Rev-I	5	4	0,02886877	7	2,26693880
C	Coop-Rev-I	5	8	0,04983440	5	2,01764855
C	Coop-Rev-I	5	14	0,03368027	9	2,07912600
C	Coop-Rev-I	7	7	0,00698273	10	2,97335547
C	Coop-Rev-I	7	8	0,00899585	3	4,72198593
C	Coop-Rev-I	7	9	0,00036646	9	5,00602746
C	Coop-Rev-I	7	13	0,04161819	8	1,97854147
C	Coop-Rev-I	7	15	0,04712476	6	1,98590417
C	Coop-Rev-I	8	7	0,04465213	3	2,47956603
C	Coop-Rev-I	8	13	0,00862070	7	3,10333857
C	Coop-Rev-I	9	3	0,02782729	8	2,23735593
C	Coop-Rev-I	9	8	0,04807354	5	2,04587070
C	Coop-Rev-I	9	9	0,02600896	13	2,13870105
C	Coop-Rev-I	9	11	0,01925228	11	2,34974587
C	Coop-Rev-I	10	3	0,00178892	4	6,13505163
C	Coop-Rev-I	10	4	0,01658027	5	2,91618154
C	Coop-Rev-I	10	6	0,01912552	6	2,64563676
C	Coop-Rev-I	10	9	0,00629018	5	3,80373372
C	Coop-Rev-I	10	10	0,02130686	7	2,47350311
C	Coop-Rev-I	10	11	0,04510887	5	2,09593282
C	Coop-Rev-I	10	14	0,03265274	5	2,35313311
C	Coop-Rev-I	11	9	0,04479927	11	1,86142784
C	Coop-Rev-I	11	11	0,03189798	13	2,02598524
C	Coop-Rev-I	12	6	0,03789702	6	2,14339686
C	Coop-Rev-I	13	2	0,03378936	8	2,11279524
C	Coop-Rev-I	13	3	0,02385147	11	2,22788142
C	Coop-Rev-I	13	10	0,04818224	5	2,04409741

Table 25: Significant Type C inter-brain coherence increase one-sample t-test results across optodes for cooperation reverse II task

Type	Social Task	opt #1	opt #2	p	df	tstat
C	Coop-Rev-II	2	10	0,00571156	6	3,59586301
C	Coop-Rev-II	3	10	0,03294242	4	2,51245127
C	Coop-Rev-II	4	1	0,04623798	6	1,99961245
C	Coop-Rev-II	4	10	0,01554284	4	3,25983424
C	Coop-Rev-II	6	10	0,01746463	5	2,87159894
C	Coop-Rev-II	11	6	0,03043379	6	2,30278610
C	Coop-Rev-II	12	6	0,03316527	5	2,34060150
C	Coop-Rev-II	12	7	0,02318127	4	2,85070955
C	Coop-Rev-II	12	8	0,03822462	3	2,65830487
C	Coop-Rev-II	12	9	0,02171680	6	2,55097350
C	Coop-Rev-II	12	10	0,03982844	4	2,33679892
C	Coop-Rev-II	14	6	0,03585320	7	2,12014250

Table 26: Significant Type D inter-brain coherence increase one-sample t-test results across optodes for competition normal tasks

Type	Social Task	opt #1	opt #2	p	df	tstat
D	Comp-Norm-I	1	12	0,00517729	8	3,33193455
D	Comp-Norm-I	2	3	0,02615269	9	2,23456586
D	Comp-Norm-I	2	8	0,03281282	7	2,18015561
D	Comp-Norm-I	2	15	0,04212144	6	2,06694455
D	Comp-Norm-I	2	16	0,04382062	13	1,84691362
D	Comp-Norm-I	3	14	0,00960367	11	2,74070150
D	Comp-Norm-I	3	15	0,04480004	9	1,90200690
D	Comp-Norm-I	4	16	0,02734126	11	2,14962585
D	Comp-Norm-I	5	8	0,03002894	5	2,42080309
D	Comp-Norm-I	5	14	0,04837123	9	1,85393974
D	Comp-Norm-I	5	15	0,03163607	7	2,20489561
D	Comp-Norm-I	6	14	0,04174275	11	1,90328077
D	Comp-Norm-I	6	16	0,04072472	11	1,91784922
D	Comp-Norm-I	14	8	0,02639912	8	2,27111788
D	Comp-Norm-I	16	8	0,03615534	8	2,06927342

Table 27: Significant Type D inter-brain coherence increase one-sample t-test results across optodes for competition reverse tasks

Type	Social Task	opt #1	opt #2	p	df	tstat
D	Comp-Rev-I	16	10	0,02567645	8	2,28890076
D	Comp-Rev-I	16	11	0,00796130	12	2,80410406
D	Comp-Rev-II	2	4	0,03880121	8	2,02377944
D	Comp-Rev-II	4	9	0,04891801	6	1,95896058
D	Comp-Rev-II	9	8	0,03616821	6	2,17723655
D	Comp-Rev-II	9	10	0,00225797	6	4,41070455
D	Comp-Rev-II	11	10	0,04418232	6	2,03244027

Table 28: Significant Type D inter-brain coherence increase one-sample t-test results across optodes for cooperation normal I task

Type	Social Task	opt #1	opt #2	p	df	tstat
D	Coop-Norm-I	2	11	0,03711904	11	1,97231215
D	Coop-Norm-I	4	11	0,02048443	9	2,38384233

Table 29: Significant Type D inter-brain coherence increase one-sample t-test results across optodes for cooperation normal II task

Type	Social Task	opt #1	opt #2	p	df	tstat
D	Coop-Norm-II	1	7	0,03806931	5	2,23027616
D	Coop-Norm-II	2	5	0,03031807	5	2,41303863
D	Coop-Norm-II	2	8	0,02231612	6	2,53078742
D	Coop-Norm-II	2	9	0,04034809	9	1,96726606
D	Coop-Norm-II	2	11	0,00347473	9	3,47900306
D	Coop-Norm-II	2	16	0,01303586	11	2,56954082
D	Coop-Norm-II	5	16	0,01535852	6	2,81096739
D	Coop-Norm-II	7	5	0,04636701	6	1,99760148
D	Coop-Norm-II	7	8	0,03177844	2	3,77496366
D	Coop-Norm-II	8	1	0,02267565	4	2,87256423
D	Coop-Norm-II	8	4	0,01216984	5	3,18725354
D	Coop-Norm-II	8	9	0,02887356	5	2,45266116
D	Coop-Norm-II	8	11	0,01240688	6	2,97446278
D	Coop-Norm-II	8	15	0,03795032	4	2,38107285
D	Coop-Norm-II	8	16	0,00213505	7	4,15466747
D	Coop-Norm-II	9	9	0,04286355	12	1,87230639
D	Coop-Norm-II	9	11	0,03331863	10	2,05775568
D	Coop-Norm-II	9	13	0,03010474	8	2,18691924
D	Coop-Norm-II	9	16	0,04550935	9	1,89217979
D	Coop-Norm-II	10	5	0,00809426	3	4,90872036
D	Coop-Norm-II	10	9	0,00921254	5	3,44051794
D	Coop-Norm-II	10	11	0,03846536	5	2,22203990
D	Coop-Norm-II	10	14	0,02617061	4	2,73188391
D	Coop-Norm-II	10	15	0,04784306	3	2,40218745
D	Coop-Norm-II	10	16	0,02203286	7	2,45064250
D	Coop-Norm-II	11	9	0,02168059	10	2,31197721
D	Coop-Norm-II	11	11	0,00663889	12	2,90196437
D	Coop-Norm-II	11	13	0,00331871	9	3,50819573
D	Coop-Norm-II	11	16	0,03375324	10	2,05001604
D	Coop-Norm-II	12	2	0,02952931	6	2,32481185
D	Coop-Norm-II	12	7	0,04150339	4	2,29925795
D	Coop-Norm-II	12	9	0,00296939	6	4,16084780
D	Coop-Norm-II	12	11	0,00064342	5	6,49980100
D	Coop-Norm-II	13	9	0,00535735	8	3,30896611
D	Coop-Norm-II	13	16	0,02181435	8	2,39332708
D	Coop-Norm-II	14	7	0,00999472	6	3,14308465
D	Coop-Norm-II	14	16	0,04148078	8	1,98067843
D	Coop-Norm-II	15	9	0,00043446	5	7,08189087
D	Coop-Norm-II	15	16	0,03126932	5	2,38804759
D	Coop-Norm-II	16	1	0,02496947	6	2,44781172
D	Coop-Norm-II	16	5	0,04044562	6	2,09629311
D	Coop-Norm-II	16	7	0,00845925	7	3,11683505
D	Coop-Norm-II	16	9	0,02305754	9	2,31160644
D	Coop-Norm-II	16	11	0,02612833	10	2,20208117
D	Coop-Norm-II	16	16	0,03724720	12	1,95332766

Table 30: Significant Type D inter-brain coherence increase one-sample t-test results across optodes for cooperation reverse tasks

Type	Social Task	opt #1	opt #2	p	df	tstat
D	Coop-Rev-I	1	1	0,03780043	13	1,93086944
D	Coop-Rev-I	1	10	0,03496426	4	2,45684167
D	Coop-Rev-I	1	15	0,03372240	9	2,07835471
D	Coop-Rev-I	2	2	0,04597064	13	1,81944537
D	Coop-Rev-I	2	4	0,02071866	10	2,33861449
D	Coop-Rev-I	3	1	0,01006660	11	2,71436521
D	Coop-Rev-I	3	2	0,00673620	8	3,15617607
D	Coop-Rev-I	3	3	0,01011056	14	2,61885287
D	Coop-Rev-I	3	4	0,00209280	11	3,59785779
D	Coop-Rev-I	3	5	0,01964754	7	2,52891714
D	Coop-Rev-I	3	6	0,02697567	8	2,25727479
D	Coop-Rev-I	3	7	0,00835155	7	3,12599130
D	Coop-Rev-I	3	10	0,00570994	4	4,43023986
D	Coop-Rev-I	3	11	0,00144166	9	4,05036934
D	Coop-Rev-I	3	13	0,04189111	11	1,90118504
D	Coop-Rev-I	3	16	0,04328047	9	1,92356327
D	Coop-Rev-I	5	4	0,01954270	7	2,53257884
D	Coop-Rev-I	5	6	0,00440402	7	3,59416774
D	Coop-Rev-I	5	10	0,00384757	4	4,96200184
D	Coop-Rev-I	5	16	0,04682204	8	1,90224105
D	Coop-Rev-I	6	10	0,01261851	6	2,96140297
D	Coop-Rev-I	7	3	0,04094815	7	2,03013639
D	Coop-Rev-I	7	4	0,00022278	6	6,93467377
D	Coop-Rev-I	7	6	0,00232176	7	4,08785065
D	Coop-Rev-I	7	8	0,01518858	3	3,87735620
D	Coop-Rev-I	7	10	0,00342662	4	5,12689897
D	Coop-Rev-I	9	6	0,01011831	8	2,88879210
D	Coop-Rev-I	9	11	0,02399553	11	2,22444074
D	Coop-Rev-I	9	13	0,04402451	9	1,91292061
D	Coop-Rev-I	9	15	0,02118661	6	2,56932931
D	Coop-Rev-I	10	13	0,01833765	5	2,82998654
D	Coop-Rev-I	11	4	0,04735508	8	1,89489069
D	Coop-Rev-I	11	6	0,02946361	9	2,16146031
D	Coop-Rev-II	1	1	0,02942221	10	2,13178120
D	Coop-Rev-II	2	2	0,04044039	12	1,90599350
D	Coop-Rev-II	3	1	0,00124337	9	4,14936107
D	Coop-Rev-II	3	3	0,04232040	12	1,87970340
D	Coop-Rev-II	7	10	0,03968158	3	2,61469484
D	Coop-Rev-II	8	9	0,01450636	5	3,03206753
D	Coop-Rev-II	12	11	0,01636525	5	2,92742175

CURRICULUM VITAE

PERSONAL INFORMATION

Surname, Name:
Birth Date:
Birth Place:
Contact:

EDUCATION

Ph.D - Cognitive Science **Jan. 2022** **CGPA: 4.00**
Middle East Technical University, Ankara, Turkey

M.Sc - Computer Science **Jan. 2010** **CGPA: 3.30**
Bilkent University, Ankara, Turkey

B.Sc - Computer Science **May 2007** **CGPA: 3.43**
Bilkent University, Ankara, Turkey

High School **2003**
T.E.D. Ankara Koleji, Ankara, Turkey

PROFESSIONAL EXPERIENCE

Year	**Company**	**Role**
2021 - Present	Juniper Networks	Software Engineer
2013 - 2021	Argela	Software Architect
2011 - 2013	Turk Telekom	R&D Engineer
2007 - 2010	Bilkent University	Teaching Assistant

SKILLS & EXPERTISE

- Over 10 years of development using C, C++, Java programming language and multi-threaded programming
- Preparation, execution and engineering of multi-national EU projects, such as FP7 & Celtic-Plus

- Experience with MATLAB, Python, SQL, REST, JSON, UML
- Research and IPR generation (5+ patents)
- Requirements gathering and analysis, system architecture design
- Project management and agile software development
- Active member of O-RAN standardization group, including rapporteur roles
- Very good understanding of wireless technologies with special focus on 4G & 5G
- IP Networking experience including TCP/IP, MPTCP, GTP, multimedia streaming, routing, iptables, OpenWRT

PATENTS

- Method and device for monitoring and measurement of Wi-Fi Internet services – US Patent 9,549,333.
- Method and system for a wireless access transmission network across intersecting electromagnetically shielded regions – US Patent 10,200,876.
- Open control plane function for wireless networks - US Patent 10,797,934.
- Apparatus and Method for a unified slice manager – US Patent 10,939,267.
- Apparatus and method for joint profile-based slicing of mobile access and optical backhaul – US Patent 10,992,385.

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- A Survey on Scheduling in IEEE 802.16 Mesh Mode, IEEE Communications Surveys and Tutorials, Vol. 12, No.2, April 2010.
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