NEURAL MECHANISMS UNDERLYING JOINT ACTION

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ABSTRACT

NEURAL MECHANISMS UNDERLYING JOINT ACTION

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The ability to engage in joint attention and perform joint actions is crucial for social life, and therefore an indispensable attribute of human cognition. It is common in everyday life that people need to perform an action together, which is called a joint action. Joint action requires extra effort compared to individual action, such as sharing mental representations, coordination, predicting partner's behavior, entrainment and perception-action matching. The setting of joint action, whether it is cooperative or competitive, affects participants' performance as well. The cognitive mechanisms underlying joint action between individuals are still under research. In this study, changes in neural activation during a social condition were investigated with hyperscanning, using functional near infrared spectroscopy (fNIRS) and electroencephalography (EEG) as participants first performed the same task individually and then as a dyad. Sixty-two participants were tested in thirty-one dyads with a dual version of the n-back task. The findings generally indicated that there was a positive correlation between the n-back level and reaction times, heart rate, and oxygenation change across the PFC; whereas task accuracy and heart rate variability decreased with the n-back level. The effect of social presence was in general smaller than the effect of task difficulty and hinted towards a lower mental workload during the social task condition. The interbrain connectivity of the participants changed with the task difficulty.

Keywords: EEG, fNIRS, Neural Mechanisms, Hyperscanning, Social Cognition.

ÖZ

ORTAK HAREKETİN SİNİRSEL MEKANİZMALARI

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Ortak dikkat oluşturma ve ortak hareket yapma kabiliyeti sosyal hayat için çok önemlidir ve bu nedenle insan bilişinin mühim özellikleri arasındadır. Günlük hayat içinde insanların yaygın olarak bir hareketi birlikte yapmaları gerekir, birlikte yapılan bu harekete ortak hareket denmektedir. Bireysel harekete kıyasla ortak hareket fazladan çaba gerektirir; örneğin zihinsel temsillerin paylaşımı, koordinasyon, ortağın hareketini tahmin etme, kenetlenme ve algı-hareket eşleme yapılır. Ortak hareketin yapısı, yani işbirliği veya rekabet şeklinde olması, katılımcıların performansını etkilemektedir. Bireyler arasında ortak hareket esnasında kullanılan bilişsel mekanizmalar hala araştırılmaktadır. Bu çalışmada sosyal bir durum esnasında sinirsel aktivasyondaki değişimler "hyperscanning" yani hipertarama denilen yöntemle incelenmiştir ve bunun için katılımcılar aynı görevi önce yalnız yapıp sonra bir ikili olarak hareket ederlerken fonksiyonel yakın kızılötesi spektroskopi (fNIRS) ve elektroensefalografi (EEG) ile kayıt alınmıştır. Altmış iki katılımcı otuz bir adet ikili halinde n-geri görevinin ikili versiyonu ile test edilmiştir. Bulgular genel olarak prefrontal kortekse yaygın biçimde n-geri seviyesi ile tepki süreleri, kalp atış hızı ve oksijenasyon değişimi arasında pozitif bir korelasyon olduğunu, görevde doğruluk ve kalp hızı değişkenliğinin ise azaldığını göstermiştir. Sosyal varlığın etkisinin genel olarak görev zorluğu etkisinden daha küçük olduğu ve sosyal durum sırasında daha düşük bir zihinsel iş yükü oluşturduğu görülmüştür. Katılımcıların beyinler arası bağlantısının görev zorluğuna göre değişkenlik gösterdiği gözlenmiştir.

Anahtar Sözcükler: EEG, fNIRS, Sinirsel Mekanizmalar, Hipertarama, Toplumsal Biliş.

To My Family

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ACC	Anterior Cingulate Cortex
AIC	Anterior Insular Cortex
aIPS	anterior Intraparietal Sulcus
ANOVA	Analysis of Variance
ASD	Autism Spectrum Disorder
BOLD	Blood Oxygen Level Dependent
bpm	Beat Per Minute
cm	centimeter
d	Cohen’s d (effect size)
df	Degree of Freedom
DLPFC	Dorsolateral Prefrontal Cortex
ECG	Electrocardiography
EDA	Electrodermal Activity
EEG	Electro-Encephalography
EMG	Electromyography
EOG	Electrooculography
ERP	Event-Related Potential
FDR	False Discovery Rate
FIR	Finite Impulse Response
fMRI	Functional Magnetic Resonance Imaging
fNIRS	Functional Near-Infrared Spectroscopy
HbO	Oxy-hemoglobin
HbR	Deoxy-hemoglobin
HRV	Heart rate variability
Hz	Hertz
IFG	Inferior Frontal Gyrus
IPL	Inferior Parietal Lobule
LSL	Lab Streaming Layer

M	Mean
MATB-II	Multi-Attribute Task Battery II
MEG	Magnetoencephalography
MNS	Mirror Neuron System
mPFC	medial Prefrontal Cortex
mV	millivolt
ms	millisecond
NASA-TLX	NASA Task Load Index
OFC	Orbito-Frontal Cortex
PET	Positron Emission Tomography
PFC	Prefrontal Cortex
PJAM	Predictive Joint-Action Model
PLV	Phase Locking Value
pNN50	Percentage of N-N Intervals that differ more than 50 ms
pSTS	posterior Superior Temporal Sulcus
RMSSD	Root-Mean-Square of Successive Differences
rTPJ	right hemisphere Temporoparietal Junction
SDNN	Standard Deviation of N-N Intervals
SE	Standard Error
STS	Superior Temporal Sulcus
SWAT	Subjective Workload Assessment Technique
TIPI	Ten Item Personality Inventory
ToM	Theory of Mind
TPJ	Temporoparietal Junction
WP	Workload Profile
WTC	Wavelet Transform Coherence
η_p^2	Partial Eta Squared

CHAPTER 1

INTRODUCTION

In daily life, humans are presented with many obstacles they cannot overcome on their own, as well as many goals which require more than one person to accomplish. These types of actions are called joint actions, and they enable people to achieve feats that are not possible for a single person (Pacherie, 2011). Joint actions involve a wide range of tasks that include communicating in a dialogue by forming joint attention, sharing references and tracking the other person's goals, or carrying objects together by coordinating movements and predicting the collaborator's behavior (Vesper et al., 2017). Performing joint action tasks usually have more requirements than single actions, such as creating mental representations of the other participant's mind (Sebanz et al., 2003), sharing interpretations of sensory information and actions (Hari et al., 2013), forming perception-action links to predict the behavior of the cooperator (McEllin et al., 2018), and coordination of movements (Vesper et al., 2011).

Joint action is very important for the members of a society to live side by side, and skill in performing joint tasks is crucial for a person's place in society. People who participate in joint tasks more often and more successfully are preferred by their peers in comparison to others who refrain from joint tasks for reasons such as shyness or fear of failure (Mein et al., 2016). Similarly, when two people act in synchrony, affective ratings they give each other are significantly higher than acting asynchronously or individually (Hove & Risen, 2009). Existence of another person putting effort into an action increases commitment to the task, as participants persisted on playing a game that incrementally become boring, if they thought there was another person playing alongside effortfully, even if they could not see or hear the person (Székely & Michael, 2018).

Joint action and joint attention are almost specific to our species even though there is a small number of studies which have results that can be suggested as signs of joint attention in chimpanzees (Okamoto-Barth & Tomonaga, 2006). Similarly, signs of motor understanding of others' behavior are detected in apes, sparrows and finches, species which are regarded to have primitive mirror neuron systems (Rizzolatti & Sinigaglia, 2010). Other researchers argue that primates are able to understand the intentions of others, although only humans are predisposed to forming shared intentionality within a group (Call, 2009).

Humans are inherently social and tend to participate in joint tasks whether they are clearly instructed to do so or not (Tomasello, 2009). Participants in dyads lose efficiency when the tasks of each participant are different but not when they do the same task (Dudarev & Hassin, 2016). This finding indicated that participants tracked and represented each other’s task even though it was not required, and when they were asked afterwards, the participants reported that they were not aware of doing so; showing that tracking another’s task might be an unintentional process.

Around nine months, babies begin to engage in joint attention, such as following gaze, and understand when joint attention is possible to establish and when it is not (Moll & Meltzoff, 2011). After the development of joint attention and ability to understand shared goals, one-year-olds show signs of motivation and ability for joint action. By 18 months, they participate in joint action and coordinate with others, such as waiting for the other person to synchronize their behavior. At the age of 3, they can commit to joint tasks and ask for permission when they want to leave the joint action, and they can also participate in several joint tasks simultaneously (Carpenter, 2009). Imitation is closely associated with joint action, and important for learning from other people’s behavior (McEllin et al., 2018). These steps of joint attention and joint action are considered as important milestones in the development of children (Milward & Carpenter, 2018).

Compared to children, adults can participate in joint tasks that are much more complex. Carrying out joint action tasks and achieving successful coordination among partners require several mechanisms. Entrainment enhances synchronization between people that prepare for a certain task together and thus allows them to time their actions, and it is suggested to work in parallel with task co-representation (van der Wel & Fu, 2015). Matching perception to action is another way to achieve coordination when people need to act together as in couples dancing. Finally, sharing representations of each other and their perceptions allows people to plan their actions to achieve harmony in any joint action (Loehr et al., 2013). Alignment is also important during a dialogue (Garrod & Pickering, 2009), which involves using similar language structures and lexicon, adapting posture, as well as gaze alignment for sharing visual attention (Shockley et al., 2009); however, too much alignment decreases success in joint tasks (Coco et al., 2018).

Current studies regarding joint action in humans usually focus on cooperation rather than competition. It is suggested that while competition is the key element of nonhuman primate sociability, cooperation is the main characteristic of human social cognition (Reboul, 2010). The main reason behind this idea is that humans, even 3-year-olds, can commit to joint goal situations regarding collaborative action, in contrast to primates who often break their commitment to the task and lose attention (Tomasello et al., 2012). Moreover, another study (Iani et al., 2011) revealed that participants who perform a task together tend to perceive the situation as if they were in cooperation, even if they are not explicitly instructed of such a condition.

This study focuses on changes in neural activation during social presence and how behavioral and physiological measures differ in accordance to the personality of the participant. The paradigm employed in the experiment is a dual version of the n-back task which covers the levels of 0-, 1-, 2-, and 3-back.

The single participant version of the n-back task (Kirchner, 1958) is a frequently used paradigm in studies focusing on working memory and mental workload (Brouwer et al., 2014; Herff et al., 2014; Parasuraman & Rizzo, 2009). Dual version of the n-back task is typically employed for investigating divided attention and multimodal processing, which is also featured in the literature as a reliable paradigm for assessment of joint action (Dommer et al., 2012; Jaeggi et al., 2008; Salminen et al., 2012).

Behavioral findings in the n-back task generally include a drop in reaction times and task accuracy (Hogervorst et al., 2014). Regarding EOG, the literature suggests that higher mental workload causes an increase in blink rate and a decrease in variability of blink rate (Gebrehiwot et al., 2016; Magliacano et al., 2020; Paprocki & Lenskiy, 2017). ECG studies show that the heart rate increases with mental workload (Wilson, 2002) whereas the heart rate variability decreases (Matthews et al., 2015).

Personality traits of participants might affect neural measures obtained in experiments. Ten Item Personality Inverntory (TIPI) has been featured in several studies and it assesses extraversion, conscientiousness, agreeableness, emotional stability, and openness (Romero et al., 2012). Previous studies used EEG data obtained during emotional stimuli for successful classification of all five personality traits (W. Li et al., 2020; Zhao et al., 2017). An earlier study found a smaller relation between the same five personality traits and EEG response to flickering light stimulation (Stough et al., 2001). EEG literature features findings for extraversion in resting state EEG (Baumgartl et al., 2020; Rahmanian et al., 2020; Wacker & Gatt, 2010), agreeableness during face expression discrimination or Flanker task (Knyazev et al., 2019; Rashid et al., 2012; Tops et al., 2006), conscientiousness during emotional processing (Imhof, 2019; Klados et al., 2020) and emotional stability in resting EEG (Jach et al., 2020).

Neuroimaging data was obtained via functional near-infrared spectroscopy (fNIRS) and electroencephalography (EEG) from both participants at the same time, and assessed with hyperscanning for alignment between two participants during the social condition. This study is among the first studies that investigate the involvement of prefrontal cortex and the changes in intra- and inter-brain connectivity measures in a social condition with the simultaneous use of fNIRS- and EEG-hyperscanning. Learning more about the nature of social cognition helps in understanding the human mind, which is suggested to have the social aspect as the default mode (Sebanz et al., 2007) and also the basis of psychiatric disorders related to the impairment in social skills (Schilbach et al., 2013).

Per-participant analysis of fNIRS, EEG, ECG (electrocardiography) and EOG (electrooculography) data were conducted alongside behavioral measures to assess any difference between Individual and Social task conditions. Combining hyperscanning with these findings provide information regarding the neural mechanism that makes it possible for humans to successfully collaborate on a time-constrained and complex task, which is a common and foundational part of social interaction.

The following chapters are organized in this structure: Chapter 2 covers the current literature on topics related to this thesis work, Chapter 3 explains the methodology of the study, Chapter 4 includes the results of analyses conducted on the data, Chapter 5 provides a discussion of findings, Chapter 6 sums up the current work in a brief overall conclusion, which is followed by a list of references, and ends with the appendices that contain the questionnaires and other forms used in the study, the ethics committee approval, and curriculum vitae.

CHAPTER 2

LITERATURE REVIEW

In this section, the current state of research will be explained for joint attention, theory of mind, joint action, mental workload, neuroimaging techniques and coherence.

2.1. Joint Attention

Attention comprises an engagement between a human and an object (Reddy, 2011). Understanding how attention works is important in research of how information is processed in cognitive systems, as attention is interpreted as the ability to select and enhance certain aspects of information which is currently processed, while other aspects are suppressed. Attention enables us to focus on the maximal possible information which we need to succeed in an activity without being overwhelmed by a very high mental workload, as cognitive resources are pointed towards most relevant events. Therefore, attention is linked with several brain regions, and almost all psychological processes require attention (Pisapia et al., 2012).

Joint attention is defined as attending to an object or scene with another person, and all parties involved should be aware of their participation (Seemann, 2011). The example given by the author is that when a person is driving a car, he or she looks ahead, and someone in the passenger seat also does the same thing. However, if the passenger suddenly turns right to look at something there, the driver’s gaze also shifts in the same direction. In human – human interaction, it is important for people to recognize the focus of other people’s attention and what they are thinking about, as well as predicting how their attention and thought would change when they are presented with something new, like a new information given in a conversation (Sperber & Wilson, 2012).

The ability to engage in joint attention and perform joint tasks is crucial for social life, and therefore an indispensable attribute of human cognition. Joint attention makes it possible to share a task with another person, learn from other people’s actions, anticipate another person’s behavior, and, if necessary, to also coordinate actions between two or more people (Sebanz et al., 2006).

Joint action requires joint attention. Children become capable of forming joint attention with other people between their first and second birthdays (Moore & D'Entremont, 2001). This changes their entire world view, and paves the way for a large set of actions that are not possible to carry out individually. The development of joint attention is heralded by gaze-following behavior (Shepherd & Cappuccio, 2011) and pointing (Racine, 2011), and as children grow, they play games, dance, and speak with their peers, which are considered to be joint actions by scholars in the field (Galantucci, 2009; Shintel & Keysar, 2009). Eighteen-months old children can successfully understand an adult's intentions, even when the adult fails during the act or the action is beyond the infant's capability, like taking apart a heavy dumbbell (Meltzoff, 2002).

The development of the ability to share representations about the environment is a key point in the development of joint attention, and a necessity for successfully performing joint action tasks (Baron-Cohen, 1991). The superior temporal sulcus (STS) is involved in theory of mind (Decety & Lamm, 2007), the prediction of other people's actions (Blakemore & Decety, 2001), as well as the mirror neurons in the premotor and parietal cortex (Sebanz et al., 2006). As shown by a functional Magnetic Resonance Imaging (fMRI) study, mirror neurons are not only active during imitation, instead, they showed even more activation during complementary action (Newman-Norlund, Van Schie, et al., 2007). It is suggested that these mirror neurons do not only reflect the observed action, but anticipate them as well (Csibra, 2007), which supports their role in joint action over mere imitation. Children who have higher activation in their mirror neuron system perform better when they cooperate with their peers, as shown by an electroencephalography (EEG) study on 29 children with a mean age of four years (Endedijk et al., 2017).

In his book titled Why We Cooperate, Tomasello (2009) suggested that no other species except humans have social institutions. He claimed that humans are born with a tendency to be cooperative, as empirical data shows that children, starting from their first birthday, outperform adult chimpanzees and other apes in helping, informing and sharing. He also described how chimpanzees might seem to cooperate during a hunt but actually still pursue individual goals, whereas human children, before the age of two, understand social norms and participate in games with abstract rules and joint goals. This innate tendency for altruism is nurtured with social upbringing and thus children become cooperative, helpful people (Tomasello, 2009).

The neural circuitry involved in joint attention include superior temporal sulcus (STS) (Decety & Lamm, 2007), cingulate cortex, and lateral sulcus (Hasson et al., 2004)(Please see Figure 1). The study by Hasson et al. (2004) showed that joint attention while watching a film together resulted in inter-brain synchronization of these areas with functional magnetic resonance imaging (fMRI). These regions take part in different but related functions as well, for example cingulate cortex is involved in empathy and link between emotional and behavioral responses (Ugazio et al., 2014).

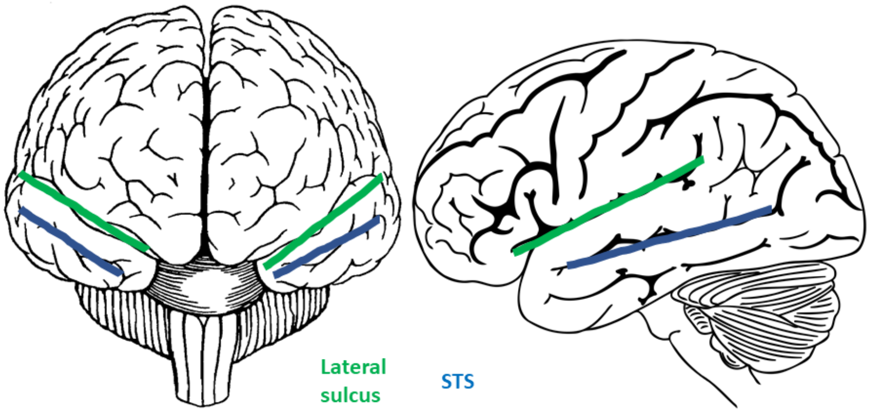


Figure 1: Brain regions associated with joint attention.

Longitudinal studies suggest that joint attention is a precursor to Theory of Mind (ToM), along with imitation abilities (Charman et al., 2000; Sodian & Kristen-Antonow, 2015). Charman and colleagues worked with 13 children, who were tested for their ability of joint attention, playing, and imitation when they were 20 months old, and then tested with a task battery of ToM tasks when they were 44 months old. Skill in joint attention tasks and gaze switching during play at 20 months showed positive correlation with success in ToM tasks, whereas imitation ability was associated with expressive language skills, and goal detection was positively correlated with receptive language skills (Charman et al., 2000). A more recent study involving 83 children which were tested at several time points between the ages of 1 and 4 featured tasks of declarative pointing, imperative production, mirror rouge test, perspective taking, and false belief. The results revealed that declarative joint attention skill at the age of 1 is an indication of understanding false belief when the child is 50 months old, independent of child's language skills (Sodian & Kristen-Antonow, 2015). Another paper (Aschersleben et al., 2008) tested the same children from a previous work (Jovanovic et al., 2007), forming a makeshift longitudinal study. In the first experiment, 24 infants with an average age of 6 months were analyzed for looking times regarding the change between scenes of two objects and an adult's hand (Jovanovic et al., 2007). The second experiment was carried out on 20 of the participants from the first experiment, who were 4 years old at that time. They were tested with a ToM task battery, consisting of knowledge access, divergent desires, false belief, and real–apparent emotion. The results showed that attention to goal-directed action around 6 months of age is a predictor for the theory of mind development (Aschersleben et al., 2008).

2.2. Theory of Mind

The mind is not something a person can directly perceive, and yet everyone knows that other people have a mind just like their own. In the literature, this assumption is called Theory of Mind and it is very important for social life and learning (Carlson et al., 2013;

Leslie et al., 2004). Through Theory of Mind, people follow each other's mental states, perceptions, knowledge, and beliefs (Bermudez, 2014). Understanding other people's mental states requires two processes that work in a complementary fashion: Detection of others' mental states via observation, and reasoning about these observed mental states for explanation and anticipation of others' behavior (Sabbagh, 2004). Same paper suggested that these two processes invoke separate neural circuitry, with detection showing right lateralization in orbitofrontal cortex (OFC) and medial temporal circuit, whereas left medial frontal region for reasoning regarding others' mental states.

In social interactions, such as cooperative game play, Theory of Mind is important for participants to coordinate with their collaborator (Yoshida et al., 2008). Alongside empathy and mirror neurons which facilitate the understanding of others' actions, theory of mind allows a person to figure out the feelings, intentions, and ideas of people (Malle et al., 2001), therefore improves social interactions (Klimecki & Singer, 2013).

Theory of Mind develops between the ages of 2 to 4 and it does not happen all at once, instead it develops by levels, and even before the age of 2, infants show signs of understanding that other people possess attention and intentions (de Villiers, 2007). There are several tasks which are used to assess this level of Theory of Mind (Wellman & Liu, 2004). These tasks investigate whether a person, usually a child, can differentiate between desire and belief, belief and false belief, knowledge and false belief. It is also suggested that the development of ToM begins earlier by imitating others (Meltzoff, 2002), and the development of the ability to understand someone's intentions by observing their action and comparing with the goals of one's own representation of the same task(Blakemore & Decety, 2001) which are closely linked with the mirror neuron system (Iacoboni & Dapretto, 2006).

After the age of 6, children begin to develop the ability of second order Theory of Mind, which is the capability of understanding another person's ToM regarding what other people know, believe and perceive. At the age of 9, the final stage of ToM begins to develop, which is the ability of understanding social faux pas and refraining from saying hurtful things (Stone et al., 1998).

Tasks that require Theory of Mind result in activation of different cortical networks depending on the nature of the paradigm, namely anterior prefrontal cortex in detecting deception (Pinti et al., 2021)and understanding how others feel and think (Roca et al., 2011), medial prefrontal cortex (mPFC) during introspection (Keysers & Gazzola, 2014; Silani et al., 2008), gaze perception (Nummenmaa & Calder, 2009) and social value in decision making (Behrens et al., 2008), temporoparietal junction (TPJ) in assessing other people's mental states (Saxe & Kanwisher, 2003), anterior cingulate cortex in guessing other people's next action (Gallagher & Frith, 2003), OFC in understanding affection (Carlson et al., 2013), but among these, right hemisphere TPJ (rTPJ) seems to be the most prominent (Decety & Lamm, 2007; Saxe & Kanwisher, 2003) (Please see Figure 2). Anterior medial prefrontal cortex and posterior cingulate cortex are involved in self-reflection, as shown by an fMRI study on 11 participants (Johnson, 2002). Among these areas, the cingulate cortex and orbitofrontal cortex are subregions in the medial frontal cortex, which is associated with social cognition (Amodio & Frith, 2006). Dorsomedial PFC is generally regarded to be associated with thinking about other people's mental states (Dieffenbach et al., 2021).

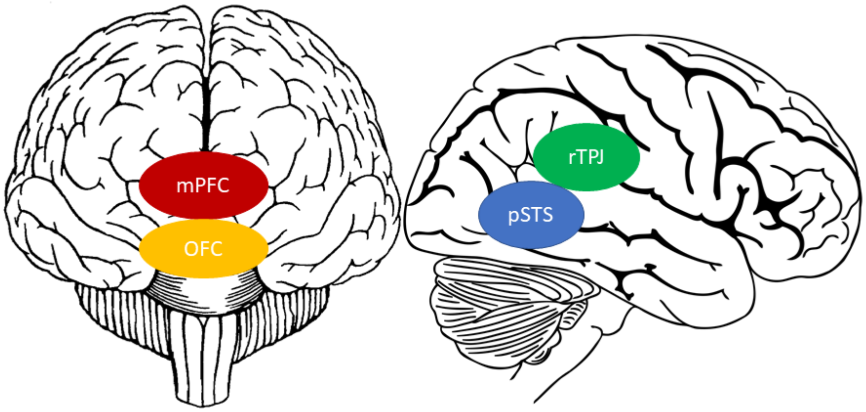


Figure 2: Brain regions associated with Theory of Mind.

Posterior Superior Temporal Sulcus (pSTS) takes part in both cooperation and competition (T. Liu et al., 2017), as well as social perception and perception of action, in addition to theory of mind (Lindquist & Barrett, 2012), so it is suggested as a key area for an integrated model covering all of these functions (D. Y.-J. Yang et al., 2015). Another study found activation in pSTS and PFC when participants were shown photographs of cooperation, around 200 ms after the display (Proverbio et al., 2011). This activation in pSTS could be attested to mirror neurons and ToM, which are thought to be closely associated systems (Klimecki & Singer, 2013). Similarly, pSTS shows higher activation in gaze contact in comparison to gaze aversion and anterior STS is responsible for understanding gaze direction (Nummenmaa & Calder, 2009), underlining the role of this region in social interactions. Another area next to STS, posterior inferior temporal sulcus, is involved in decoding actions into motor representations, which are integrated with data from inferior parietal lobule (IPL) and inferior frontal gyrus (IFG) by STS (Thompson & Parasuraman, 2012).

Failure in Theory of Mind tasks are usually linked with Autism Spectrum Disorder, and literature shows that lesions to brain areas linked to ToM produce autism-like symptoms, similar to the link between discrepancies in mirror neuron system and autism (Iacoboni & Dapretto, 2006). Bilateral OFC damage results in similar task performance to people with Asperger's syndrome, which is on the mild scale of autism spectrum and usually fails to avoid faux pas (Stone et al., 1998). On the other hand, the same study showed that unilateral left dorsolateral PFC lesions do not result in failure at ToM tasks. Deficits in joint attention capabilities are considered as the earliest signs of ASD (Baron-Cohen, 1991) and new models regarding the nature of ASD centers around impairments of social information integration (Zaki & Ochsner, 2012), even though classically ASD is characterized with problems of assigning mental states to others (Ramnani & Miall, 2004).

Cognitive models have been developed for Theory of Mind (Hiatt & Trafton, 2010). The model by Hiatt and Trafton (Hiatt & Trafton, 2010) is based on hybrid cognitive architecture ACT-R and focuses on the Sally-Anne task (Baron-Cohen et al., 1985) which is a false belief task. The model is tested for the age of 32 months to 92 months in seven-month periods. Results suggest that the model shows good fit with data from real children, and authors argue that it can be generalized to all false belief tasks.

2.3. Joint Action

It is common in everyday life that people need to perform an action together, which is called a joint action. There are two types of joint action: emergent and planned (Knoblich et al., 2011). In the emergent joint action, participants act in similar ways because of shared perception-action couplings, and in the planned joint action, participants act in a coordinated way as a result of pursuing the same goal. Some scholars argue that instantaneous coordination, which occurs in emergent joint action and seen in simple motor tasks such as finger tapping or rotating, stems from perceptual representations and not motor processes (Mechsner et al., 2001).

Joint action requires additional processes which aid in the reduction of high demand on cognitive resources (Pacherie, 2011), such as sharing mental representations, coordination, predicting partner’s behavior, entrainment and perception-action matching. All of these requirements usually cause a decrease in the participants’ reaction speed and task accuracy in tasks even as simple as carrying a stick together in a virtual environment with force sensors, which suggest an increase in mental workload (Bosga & Meulenbroek, 2007).

Shared representations, also called co-representations, mean that when two or more people carry out a task together, they represent each other’s minds, with their perceptions, goals and probable actions, in their own minds (Sebanz et al., 2005). Observing other people's actions affect our own, and when they share a task, humans can successfully predict what the other people are going to do as they coordinate their actions, and therefore, agency might be lost during a joint action task (Sebanz et al., 2006). For example, a previous study investigated complementary action with a task of responding to numbers as odd or even with different keys found that a joint Go/No-Go task results in similar reaction times to an individual two choice task instead of an individual Go/No-Go task (Atmaca et al., 2008). When groups are interacting with each other, these representations occur at the group level, such as watching an expert couple as they dance and trying to imitate them, because only following a single person would not enable prediction of partner’s moves and impair coordination (McEllin et al., 2018). Cognitive models of understanding other people’s intentions feature shared representations as well (Dindo & Chella, 2013).

An earlier study suggested that task co-representation begins at the planning stage (Kourtis et al., 2014). EEG data was obtained from 16 participants as they performed a joint action with a confederate. The joint action consisted of clinking two beer glasses. Two event-related potential (ERP) signals were analyzed to investigate the planning process of the joint action: anterior directing attention negativity and late directing attention positivity. The analysis of data indicated that participant's attention was divided between the locations of their own action and their partner's action, before the action occurred, as if they were planning a bimanual action. Furthermore, the participant's neural network regarding his/her own motor system was engaged in representing the partner's upcoming action too, as indicated by slow rising movement related potentials.

Another study (Sebanz et al., 2003) showed that an individual's actions are represented in the other participant's mind as soon as they begin the task and these representations have an impact on their actions. In that study, participants' reaction times were measured during the Simon task, which is a spatial compatibility task. The results indicated that having someone sit beside you does not affect your performance; but doing a task side by side, even when there is no feedback, affects the outcome. As shown by a previous study on 36 participants with a bimanual paradigm of circle and line drawing (della Gatta et al., 2017), coupling of motor actions occurred in dyads that performed in a joint fashion and not in dyads that did the same task in parallel but independently, which supported the claim that joint goals lead to shared motor representations in dyads.

Further studies on task co-representation revealed that these representations include each other's task constraints (Schmitz et al., 2017) and the order of action in the dyad (Schmitz et al., 2018). In the 2017 study, the participant who did not have any obstacles for his/her task still moved as if there was an obstacle (Schmitz et al., 2017). The 2018 study consisted of six experiments with similar setups, as in all of the experiments two people moved separate objects side by side to a short or long distance in different sequences (short first - long afterward, or the opposite) and the results showed that dyads who did the task with the same order had significantly shorter movement times, regardless of having a joint goal or not (Schmitz et al., 2018).

Co-representation is reported to occur during lexical tasks as well. An ERP study tested 36 participants, in dyads with a confederate, on a lexical task that consisted of 150 pictures. The participant and confederate named 50 pictures each, based on the background color, and the other 50 pictures were no-Go trials without any response. Another block of the same task was performed individually. The results indicated that participants were slower during their Go trials in joint condition versus individual condition, which might be due to the workload increase by task co-representation. Similar ERP measurements were observed when the confederate viewed a low or high frequency word and participants themselves viewed a word in the same frequency, which was absent in trials neither was supposed to respond, further supporting task co-representation (Baus et al., 2014). In a similar study, twenty-four pairs were tested with 165 photographs as they named the item in them, and reaction times showed similar latencies whether an item in the same category was presented to the participant or the other person in the dyad

(Hoedemaker et al., 2017). Another study on 72 participants found a similar effect even if the participant could not hear or see the other person, but merely believed the existence of a co-actor (Kuhlen & Abdel Rahman, 2017). Taken together, these findings support that speaking in a joint manner affects lexical retrieval and language production process.

Several cognitive models have been developed on joint attention and joint action. There are computational (Pesquita et al., 2018; Wolpert et al., 2003), connectionist (Mundy et al., 2009), and hidden Markov models (Borzeshi et al., 2013). Wolpert and colleagues' model did not feature task co-representation, which was in contrast with Vesper and colleagues' minimal cognitive architecture for explaining the processes in joint tasks (Vesper et al., 2010). A paper by Pesquita and colleagues (Pesquita et al., 2018) suggested a hierarchical predictive processing model they called the predictive joint-action model (PJAM). PJAM includes three levels of processing, which are goal representation, action-planning, and sensory routing. Task co-representations were suggested to occur at the level of goal representation. Overall, PJAM was compatible with empirical data, Wolpert et al.'s general framework regarding sensorimotor processes during social interactions and Vesper et al.'s minimum requirements of an architecture for joint action.

Another model for joint action (Please see Figure 3) focuses on how one participant can predict the movement of the other participant (Pickering & Garrod, 2013). In this model, the observer uses a covert imitation of the situation and possible actions of the other participant to generate a forward action model, which can be compared with the other participant's action later. The "t" in the model stands for time, "u" stands for action command, and "a" stands for act. For successful joint action, this prediction should work both ways as each participant should predict the action of the other.

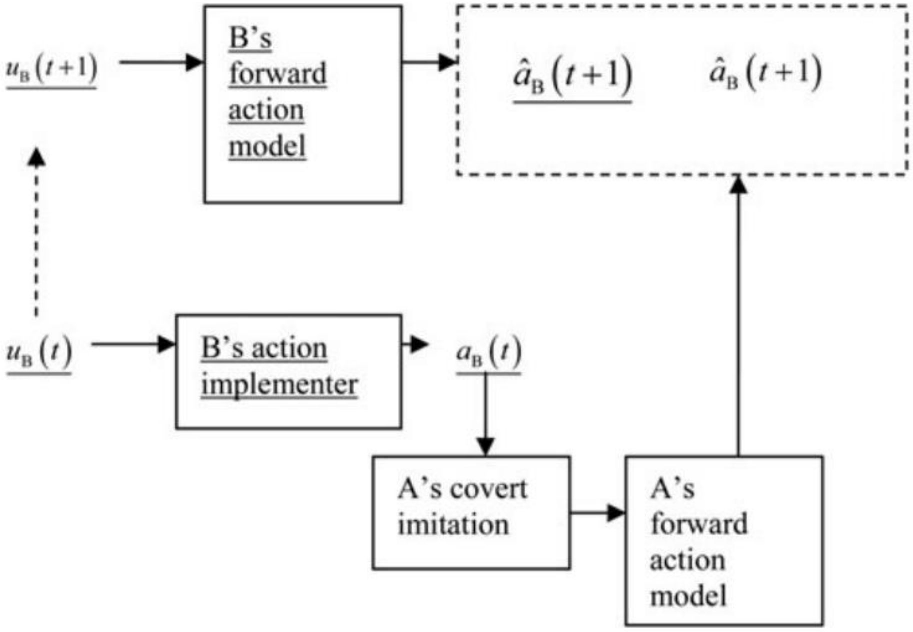


Figure 3: A cognitive model for joint action (Pickering & Garrod, 2013, p. 8).

Coordination between participants is a must for joint action (Pacherie, 2011). In the literature; coordination between individuals during joint action is investigated by methods such as physiological measures, neuroimaging techniques, video analysis, and motion tracking (Cornejo et al., 2017). As shown by experiments, people either intentionally or unintentionally reduce the temporal variability of their actions in order to facilitate coordination and increase the level of success in joint tasks (Vesper et al., 2011). The same study also showed as the number of possible actions decrease, it gets easier for participants to move together accurately. This effect is observed in cases when participants act simultaneously or sequentially, however, when people carry out different tasks next to each other the effect is absent. A similar recent study revealed that when communication is possible, it is preferred instead of reducing the temporal variability, but if there is no other way to achieve coordination, dyads reduce the variability of the timing of their movements as a simple strategy (Vesper et al., 2016).

In a recent study (Curioni et al., 2019), researchers used a task which was developed to investigate temporal coordination under spatial incongruency. Across three experiments with 10 dyads, participants drew two squares simultaneously, one each, and these squares either aligned (congruent condition) or had a 45° difference (incongruent condition). Results indicated that if the participant's drawings were visible to each other, they achieved synchronization in both congruent and incongruent trials, but still coordination was better in congruent trials.

The role (leader – follower) or background (expert – novice) of participants also affect how they achieve coordination. When 12 expert pianists were paired with 12 participants who did not play piano before, behavioral results showed that experts identified timing errors of novice players and played accordingly in order to achieve coordination (Wolf et al., 2018). Similarly, another study revealed that the leader in a joint task gave nonverbal signals to the follower as the leader showed the follower how to grasp and raise an experiment object shaped like a bottle, and the follower imitated the leader’s actions (Candidi et al., 2015). In another study with parallel results, when dyads were tested with a synchronous bottle grasping task, the participant who received the instruction concerning which point should be grasped showed a decrease in their movement variability and tried to signal the other participant about the goal, regardless of not being explicitly told to be communicative. On the other hand, the participant who received the instruction about whether the action should be in complementary or imitative fashion but not where should be grasped imitated the leader in both conditions, even though it impaired performance in complementary trials (Sacheli et al., 2013).

The effects of joint action are seen in a wide range of experimental paradigms. One of these paradigms, the Navon task (Navon, 1977), consists of responding to stimulus on either local or global aspects, and a joint Navon task is implemented in the literature as either having both participants focus on the same aspect (both global or both local) or instructing participants to focus on different aspects (Böckler et al., 2012). The results of this study revealed that participants were sensitive to each other’s attentional focus, as reaction times were slower when they focused on different aspects.

For successful coordination during a task, participants need to (a) predict what their partner will do, so they can understand his/her intention, (b) when will s/he do that action exactly, so they can move together or in a complementary fashion, and (c) where will that action occur, so that they can distribute the common space among each other (Sebanz & Knoblich, 2009). A recent study which compared performances of dyads against individuals in a simple computer game that consists of keeping a dot in a rectangle by pressing left and right buttons revealed that coordination in a dyad can be contingent and complementary (Jordan et al., 2018). During successful coordination, synchrony was detected in heart rate and skin conductance of partners, hinting at a physiological basis for achieving interpersonal coordination (Cornejo et al., 2017). This is not limited to interaction in pairs, as a previous study collected data from a choir of twelve persons, one conductor and eleven singers, synchrony was detected at heart rate and respiration rate variability of all members of the choir as they sang together (Müller & Lindenberger, 2011).

Entrainment and perception-action matching are common ways of facilitating coordination and increasing success in joint tasks. Lexical entrainment occurs between partners in a dialog (Brennan & Hanna, 2009), as speakers adapt to using the same vocabulary for referring to their environment, and this effect carries over to their interactions with others as well. In another study (Ramenzoni et al., 2014) four experiments were conducted which consisted of watching and repeating a pattern of finger tapping. The aim was to understand how joint action is mapped in human cognition depending on whether the person participates in or only observes the joint action. The results revealed that perception-action links were formed when a person imitates the temporal and spatial structure of other people's joint actions, and gender does not affect the outcome. Another study with finger-tapping found increased neural synchrony on left PFC when one participant imitated the other in comparison to acting independently, even though they sat on the same table and faced each other on both conditions (Holper et al., 2012). This relation between body movement synchronization and neural synchronization is reciprocal, as an EEG-hyperscanning study on 20 participants showed that when participants were trained before the experiment to reach better synchrony during a finger tapping task, level of neural synchronization was a predictor of cooperative task performance (Yun et al., 2012).

An hyperscanning study with electroencephalography (EEG) obtained data from people as they spoke to each other in a dyad (Pérez et al., 2017). Analysis of neural oscillations revealed brain to brain synchrony between people as one listened to the other. This synchronization was determined on phase locking value (PLV) information, which was gathered by EEG-hyperscanning, and PLVs on all four EEG bands (alpha, beta, gamma, theta) displayed synchronization. This finding suggested brain to brain entrainment during oral narratives.

Brain to brain coupling occurs during social interactions such as verbal communication (Spiegelhalder et al., 2014) as shown by a study on 11 dyads of female friends that were investigated as they spoke about their personal lives while both were under fMRI recording, with the help of noise canceling headphones and fiber optic microphones to overcome noise of fMRI machines. An fNIRS study on 48 participants, studied in groups of four, also found synchronization in PFC during verbal communication (Nozawa et al., 2016). Very similar brain to brain couplings occurred in nonverbal communication like face expressions and gestures (Hasson et al., 2012), as inter-brain Granger causality analysis showed similar temporal variation in brain activities of the observer and signaler. Another study corroborated these findings as fMRI-hyperscanning on 34 dyads showed brain-to-brain couplings in rTPJ during nonverbal transfer of information (Bilek et al., 2015). In an fNIRS study with 97 same gender dyads, higher inter-brain synchronization was detected at right temporoparietal junction when participants face each other during the Ultimatum Game in comparison to when they could not see each other's faces, and this synchronization correlated with choices of cooperation in the game, which is also in line with the role of rTPJ on nonverbal social interaction (Tang et al., 2015).

Some researchers argue that brain to brain coupling is a separate process and occurs in addition to mirroring and alignment (Hasson & Frith, 2016). Notwithstanding, other scholars claim that brain to brain coupling during verbal interactions is a sign of alignment itself and shows the aligning of shared representations of the situated model (Schoot et al., 2016) and these couplings can be studied further to identify neural circuitry regarding encoding and decoding of linguistic information. In sum, literature agrees on the existence of inter-brain couplings during communication, and discussion is focused on whether this is a distinct process that is aligned or intertwined with it.

A study investigated syntax in conversation among 90 pairs of participants as they described each other's actions from videos which had different syntactic categories (W. Liu et al., 2019). Optodes were placed on two sides of the head, corresponding to T3 and T4 in 10-20 system of EEG placement and simultaneous fNIRS data was collected with ETG400 Optical Topography System (Hitachi Medico Co., Tokyo, Japan) at 10 Hz. Their findings indicated shared representations of syntactic structures among participants and inter-brain synchronization located at the right hemisphere posterior superior temporal cortex.

Brain to brain coupling is not specific to verbal communication but seen in other social interactions. An EEG-hyperscanning study on 22 romantic couples (Goldstein et al., 2018) reported that brain to brain coupling in the alpha band (8 - 12 Hz) was detected during handholding and had analgesic effects when pain was administered to female participant's forearm in the form of heat, whereas no significant effect of pain or handholding was detected on mutual gaze count or total mutual gaze duration. Another study showed brain to brain coupling within dorsolateral prefrontal cortex (DLPFC) during cooperation, which was lost if negative feedback was given regarding the dyad's success (Balconi, Vanutelli, et al., 2018).

When a person observes another doing something, or sensing something such as being touched, same neural circuitry for the observed person's sensorimotor activation is represented in the beholder's sensorimotor cortex (Keysers et al., 2010) along with inferior parietal lobule (IPL) and inferior frontal gyrus (IFG); which is dubbed the Mirror Neuron System (MNS). General consensus on the matter is that MNS enables the beholder to understand and imitate the observed behavior (Gallese et al., 2004; Lamm & Majdandžić, 2015) and therefore facilitates joint action and builds empathy. For example, a transcranial magnetic stimulation study showed that neural circuitry regarding the same action is activated as athletes watched and predicted the outcome of a sports video, which resulted in higher success rates in their prediction, but only if they are experienced in the same sport (Aglioti et al., 2008). In another study, similar patterns of IFG activation were detected with fMRI for doing or seeing the same action (Kilner et al., 2009), and watching videos of a needle penetrate someone's hand or foot resulted in activation at sensorimotor cortex, on the same area where sensory information is processed for that body part (Avenanti et al., 2005). Nevertheless, there is another opinion that the function of this neural circuitry is not empathy or joint action, but instead, the understanding of action concepts (Jacob, 2009).

Mirror Neuron System is thought to play an important role in simulating a collaborator's actions as if one's own and using that information to successfully coordinate with that person in a joint action (Bekkering et al., 2009), similar to simulating the observed state of another person in order to understand their current emotion in empathy (Klimecki & Singer, 2013). Another function suggested for the MNS is the development of understanding self-other distinction (Milward & Sebanz, 2016). There are two views on how this self-other distinction is handled. An fMRI study on 12 participants suggested that the dorsal premotor cortex is activated when someone prepares to make an action but when that action is anticipated from another person, ventral premotor cortex is activated (Ramnani & Miall, 2004). A transcranial magnetic stimulation and electromyography study on 18 participants featured an experiment regarding finger tapping suggested a corticospinal pathway is primed when an action is observed as well as planned, but this priming is inhibited if the action belongs to another person (Roberts et al., 2018). Alongside anterior insula and anterior cingulate cortex, IPL and IFG are also involved in strengthening the bond between parent and child (Feldman, 2015). Activation is detected in MNS with fMRI in another study which featured placing rods in an instructed angle as pairs (Kokal et al., 2009). All these works support the role of MNS in joint action and empathy over Jacob's suggestion (Jacob, 2009) regarding action concepts.

The localization of Mirror Neuron System is still under debate, as some researchers suggest that neural mechanisms underlying this overlap shows right lateralization (Newman-Norlund, Noordzij, et al., 2007), although left hemisphere is associated with MNS in the literature (Rizzolatti & Arbib, 1998). Similarly, neural correlates of empathy are still under research. Recently, scholars suggested that empathy has two different subsystems: Understanding other people's perspective requires the involvement of ventromedial PFC, whereas inferior frontal gyrus is important for sharing of emotions, as shown by a study with patients who have lesions on the respective brain regions and display impairment in related empathy skills (Shamay-Tsoory et al., 2009). Empathy is regarded as an important facet of understanding the difference between representations that either belong to self and others, therefore important for self/other distinction and joint action research (Ugazio et al., 2014).

An fMRI study, which simulated balancing a ball cooperatively by squeezing force sensitive pads, reported that regions associated with MNS showed higher activation values in cooperative conditions when compared to doing the same task alone (Newman-Norlund et al., 2008). IPL is also a part of the MNS (Gallese et al., 2004), and serves to recognize the goal of the actions of others, which allows for guessing the intentions of others (Fogassi et al., 2005; Iacoboni & Dapretto, 2006). Anteromedial PFC and IFG are also parts of both systems (Yamasue et al., 2008).

There are several commonly-used psychological experiment paradigms, such as the Simon task (Simon & Rudell, 1967), the Stroop task (Stroop, 1935), and the n-back task (Kirchner, 1958), which have joint action implementations as well. In an example of visuospatial joint n-back task, participants keep track of separate squares on a grid, color-coded for each person (Dommer et al., 2012). In their joint n-back task, participants sat in front of a single computer side by side and one participant tracks the movements of a blue square on a 3x3 grid whereas the other participant tracks the movements of a green square on the same grid. The test started as 2-back and increased by one each time the players succeeded in 80% of a trial block, up to 5-back. The data from fNIRS-hyperscanning showed that participants in the joint tasks achieved between-brain connectivity, similar to the study by Cui et al. (X. Cui et al., 2012). Furthermore, synchronization was also detected between heart rates of participants in the same dyad, suggesting a possible effect of cooperation on heart rate coordination.

In the joint Simon task, each participant responds to the stimuli based on the aspect which is not spatial, and the Simon effect is preserved (Usal, 2016). In this study, 90 participants were studied in three different groups: Individual group, Cooperative Group and Competitive Group. All groups showed similar reaction times and error rates in the Simon task, however, both joint task groups reproduced significantly shorter durations when instructed to push a button as long as they thought the previous trial had lasted. According to the Attentional Gate Model of Time Perception (Zakay & Block, 1995), this finding suggested an increase in mental workload, which might have been due to sharing of mental representations (Sebanz et al., 2003). There are other manipulations that can be made on the joint Simon task, such as employing two different shapes which appear at the same time and assigning each to a participant so it will not be a Go/No-Go task (Klempova & Liepelt, 2016), and results indicated that while the Simon effect was preserved in both methods, the difference in reaction times was larger in the Go/No-Go version compared to the trials in which both participants were active. The authors argued that their findings are not in line with the task co-representation hypothesis.

Both the joint Simon task and joint Stroop task can be conducted with a single computer screen and different buttons of the keyboard or two joysticks, same as the setting of the joint n-back task. The joint Stroop task is similar to the joint Simon task, as two participants are assigned to different colors in the task and respond accordingly (Demiral et al., 2016). The results of this study supported the hypothesis that people form mental co-representations when they share a task. However, mental co-representations are still under debate. A study showed that the Stroop effect is stronger in the joint condition but stated that whether mental representations are shared is inconclusive (Yamaguchi et al., 2018). A similar study which featured joint task switching reported that the task switch costs are not affected by joint setting (Yamaguchi et al., 2019) in lieu of other studies which suggest that additional task switching costs in joint action is due to a social effect (Liefooghe, 2016). Moreover, a recent study replicated the finding that the Stroop effect is more salient in a joint setting but argued that it is not due to mental co-representations, because the same effect was achieved when the task was shared with computer or a person did half of the task and simply waited during the trials of an absent collaborator (Saunders et al., 2019).

Some studies feature novel tasks for investigating cooperation. One of the first studies that obtained simultaneous fNIRS data from both participants in the dyad at the same time (Funane et al., 2011) instructed people to count to 10 seconds in their mind and press a button as synchronized as possible, with audio feedback regarding their success after each trial. Data from twelve participants showed that inter-brain coherence of brain activity recorded by fNIRS between participants was negatively correlated with the amount of duration between their button presses, participants who achieved higher inter-brain synchronization pressed their buttons more closely, which means they cooperated better. On the other hand, a study which featured setting up a table for dinner as a joint task showed that if the joint action does not require cooperation but participants act by taking turns instead, inter-brain coherence is not observed (Egetemeir et al., 2011) and high levels of activation is detected at inferior parietal lobule, probably due to mentally simulating the other participant’s actions during observation.

In Prisoner’s Dilemma, the outcome depends on whether participants collaborate or tell on each other. An earlier study (Astolfi et al., 2011)found that right inferior frontal gyrus and left orbitofrontal cortex showed higher activation during cooperation, in comparison to right supramarginal gyrus and dorsolateral prefrontal cortex activation when participants betrayed the other. Another study featuring Prisoner’s Dilemma scanned 26 dyads with EEG and analyzed the data with graph theory (Fallani et al., 2010). The results indicated that cooperating dyads have activation in similar brain networks whereas defecting participants displayed distinct modules of active neurons. Another study (Astolfi et al., 2010) applied the same methodology of EEG, graph theory and Granger-causality analysis on 14 dyads who played a card game and showed a two-way effect between mPFC recordings of one participant and anterior cingulate cortex of the other participant in the dyad as one recording could be used to estimate the other. These two areas are related to risk taking behavior and decision making in games and gambling. These results are in line with a similar previous study on the same game with 22 participants, which found activation in mPFC in social conflict and anterior cingulate cortex (ACC) if the participant is planning to defect (Babiloni, Astolfi, et al., 2007). Placement of participants in a Prisoner’s Dilemma game had an effect on the outcome, as an EEG-hyperscanning study on 10 pairs indicated that if they could see each other’s faces, they are more likely to pick the cooperative option instead of defecting, and inter-brain synchronization is detected at right temporoparietal region.

The Ultimatum Game is basically a decision task in which two participants either successfully divide a sum of money or neither gets the reward. Interestingly, literature suggests that people refuse offers below twenty percent and prefer having no reward to "being ripped off" and accepting a 20 to 80 split. This does not make sense because 20% is bigger than zero, and it suggests possible involvement of emotional processes on the decision. In this study, authors found similar behavioral results and high activation was detected in anterior insula, which is part of the limbic system and emotional control, with dorsolateral prefrontal cortex (DLPFC), an area known to be involved in goal directed executive control (Sanfey et al., 2003).

The setting of joint action, whether it is cooperative, competitive, or a leader-follower relation, affects participants' behavior. Studies on children show that cooperative games increase motivation by providing more ways to achieve success than individual ability, whereas competitive games increase motivation by ambition, and thus competition results in higher arousal levels due to pressure of personal performance (Marker & Staiano, 2015). Brain regions linked to cooperation and competition differ as well, a study involving 22 dyads and featuring a turn-based game of placing colored disks (T. Liu et al., 2017) reported that interbrain synchronization was detected at right pSTS in both cooperation and competition, whereas right IPL and IFG showed synchronization only during competition.

Another study (Glover & Dixon, 2017) investigated the effects of cooperative and competitive settings on participant's behavior regarding predictability. Thirty-two pairs were studied with a task of pressing a button after hearing a tone, in the cooperative condition the first participant tried to minimize reaction time of the second participant whereas in the competitive condition the first participant tried to maximize it. The results showed that the first participant acted in a consistent fashion to increase predictability and facilitate the second participant's timing, and on the other hand, the first participant behaved in an unpredictable manner to disrupt the second participant.

Most studies regarding joint action focus on cooperation, however, competition is also a way to participate in the same action. A 2010 study showed that both cooperation and competition trigger mental co-representations (Ruys & Aarts, 2010). This study revealed that shared action representations are necessary for the assessment of the partner's performance, whether the performance has a positive or negative effect on the outcome for the participants themselves. Still, there are differences regarding neural mechanisms underlying cooperation and competition. In another study, twelve participants were scanned with fMRI while they played a simple computer game similar to checkers with other individuals through the internet. The setting was either cooperation or competition, and the other player was shown with a brief video clip before the game to enhance the social effect. The results revealed a significant difference between cooperative and competitive conditions in brain regions with highest activation: Bilateral insula and posterior cingulate cortex, and right anterior frontal cortex during cooperation; bilateral medial prefrontal cortex and right superior frontal gyrus during competition condition (Decety et al., 2004).

Whether the co-actor behaves according to the cooperative or competitive settings also influences the way people behave in the joint action. When six male and six female participants grasped wooden blocks with a female confederate, the confederate acted either congruently or incongruently with the task's cooperative or competitive setup, and motion analysis system showed that participants acted not according to their given instructions but instead behaved in the same setting as the confederate (Becchio et al., 2008).

Playing music together is regarded as a form of nonverbal communication (D'Ausilio et al., 2015) and therefore featured in social interaction studies. A recent study (Vanzella et al., 2019) investigated violinists with functional near-infrared spectroscopy (fNIRS) as they played duets and solo pieces. The results showed that the violinists who were in the follower position in the duet had greater activation in temporoparietal areas compared to playing solo, whereas the lead violinist did not have such a significant difference, indicating that these areas might be involved in synchronizing oneself with another and catching up to the leader's pace. Another study that scanned 15 dyads with fNIRS as they sang or hummed a tune either cooperatively or alone (Osaka et al., 2015). Calculation of interbrain wavelet transform coherence indicated that neural synchronization was higher when participants acted together, regardless of whether they faced each other or a wall. This synchronization was located at the left inferior frontal cortex.

The effect of the joint setting also depends on the emotions between the participants that are performing the joint action together. Social warmth and competence between individuals that share a task affects their behavioral and emotional responses (Fiske et al., 2007). Competition might result in negative feelings between participants, which carry over to any following task even if that task is not competitive (Iani et al., 2014). Other scholars suggest that co-representation only occurs if co-actors have a positive relationship (Hommel et al., 2009).

Finally, social facilitation is another factor that affects cognitive performance (Guerin, 2010). The difference between joint action and social facilitation is that during joint action, participants share aspects of the task they are given and perform together, whereas in social facilitation participants carry out the task in the same environment but perform independently and do not interact with each other. Social facilitation increases individual performance during simple tasks, but in contrast, performance is impaired in complicated tasks. Several reasons have been suggested as the reason behind social facilitation, including increase in drive, fear of being evaluated, and distraction. For example, performing the Stroop task in social presence results in faster responses for both congruent and incongruent words and thus a decrease in Stroop interference (Huguet et al., 1999).

Overall, the related literature suggests that the following neural circuitry is involved in cooperation: Posterior superior temporal sulcus (T. Liu et al., 2017), bilateral insula and posterior cingulate cortex, and right anterior frontal cortex (Decety et al., 2004), right dorsomedial PFC and right middle and superior frontal gyrus (N. Liu et al., 2016). Interbrain neural synchronization is detected at the left inferior frontal cortex during dialogue (Jiang et al., 2012) and cooperative singing (Osaka et al., 2015) (Please see Figure 4). On the other hand, the following areas are more active during competition: bilateral medial PFC and right superior frontal gyrus (Decety et al., 1994), pSTS, right IPL and IFG (T. Liu et al., 2017).

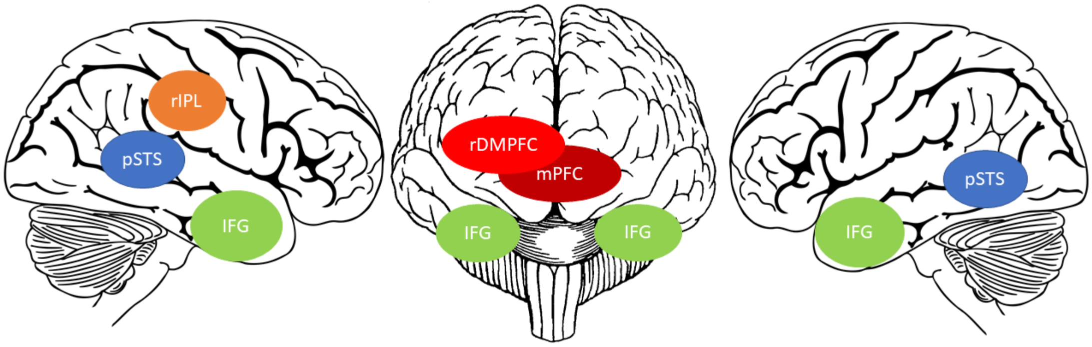


Figure 4: Brain regions associated with cooperation.

In addition, left anterior intraparietal sulcus (aIPS) is associated with goal representation (Tunik et al., 2007), sharing goal representations and prediction of partner’s behavior during complementary action, which enables the integration of each participant’s goals into one motor representation (Sacheli et al., 2015). Ventral striatum, which is usually associated with reinforcement learning, is also active during social interactions, probably for reward assessment regarding cooperation with the interacted person (Behrens et al., 2009). Premotor ventral cortex is reported to take part in joint action as well (Sebanz & Frith, 2004). An fMRI study showed activation differences in the ventromedial frontal cortex and anterior cingulate cortex, as participants performed the same go/no-go task with a confederate who also performed or just sat with her finger on the response button without reacting (Sebanz et al., 2007). A part of the neural network regarding the reward system is suggested to be specific to social rewarding situations such as altruism, as an fMRI study on 36 female participants who played an iterative version of Prisoner’s Dilemma with a female confederate had high activation patterns in orbitofrontal cortex, rostral anterior cingulate cortex, and anteroventral striatum compared to a control condition of receiving money reward without a social condition (Rilling et al., 2002).

Some researchers claim that the localization of inter-brain synchronization during joint action is associated with the nature of dependency in joint action, and synchrony emerges at mirror neuron system during interdependent joint action, whereas at PFC during independent cooperation with concurrent but separate contributions towards a common goal (T. Liu & Pelowski, 2014). A transcranial stimulation study on sixty participants also showed that when alternating current was applied over the left motor cortex and 20 Hz beta band oscillations were induced, dyads who performed a finger tapping task together have enhanced interpersonal synchrony. Such an effect was not observed in stimulations with 10 Hz or 2 Hz, which suggested a link between neural oscillations of a certain frequency in the left motor cortex and synchronization among individuals (Novembre et al., 2017).

2.4. Mental Workload

The jury is still out on the definition of mental workload. Basically, it is the cost on cognitive resources as one performs a certain task (Kramer, 1990), or in other words, the cognitive demand of the task at hand (Miyake, 2001). A simple explanation of mental workload can be given as how much of the cognitive capacity is used and how much is left as spare capacity to perform other tasks (Reid & Nygren, 1988). The exact term is still undetermined; in the literature it can also be referred to as mental load (Dan & Reiner, 2018), cognitive load (Paas et al., 2003) or cognitive workload (Hughes et al., 2019). Difficulty of the task and time pressure are claimed to increase mental workload in an additive manner, and this effect is modulated by alertness (Galy et al., 2012).

Many experimental paradigms, including the n-back task (Solovey et al., 2014), Stroop task (Lavie, 2005) and visual search task (Putze et al., 2010), as well as a wide range of real-life actions from working in a factory (Ma et al., 2012) to flying a jet (Yao et al., 2008) has been featured as methods for investigating mental workload; however, almost the entire literature is based on individual actions. Driving simulators and flight simulators are very frequently studied for the estimation of workload because of the probable relation between high mental workload and accidents (Borghini et al., 2014). For example, an fNIRS study suggested that risk taking behavior in young drivers is associated with lack of PFC maturation (Foy et al., 2016). Another application area of mental workload is the development of better educational materials (Paas et al., 2003).

Various measurement methods have been implemented for the assessment of mental workload. In the earlier days of the field, subjective measurements like NASA Task Load Index (NASA-TLX), Subjective Workload Assessment Technique (SWAT) and Workload Profile (WP) were regarded to be more accurate than objective methods (Rubio et al., 2004). Nowadays, with improvements in technology, physiological measures, including fNIRS (Herff et al., 2014), EEG (Dehais et al., 2018), fMRI (Danti et al., 2018), ECG (Mehler et al., 2009), electrodermal activity (EDA) (Ghaderyan & Abbasi, 2016), gaze measures from either EOG (Mangina et al., 2000) or eye-tracking systems (Mandrick et al., 2016), respiration rate (Novak et al., 2011), and body temperature (Jimenez-Molina et al., 2018) are becoming stronger and therefore more popular (Brünken et al., 2010).

In addition to studies that contained a single measure, there are studies which applied multiple physiological measurements together (Hogervorst et al., 2014; Wilson, 2002). Hogervorst and colleagues used ECG, EEG, EDA, respiration rate, pupil size and blinking rate for evaluating mental workload during the n-back task. Most successful single measure for discriminating 2-minute intervals of high and low mental workload was EEG data obtained from the electrode located at Pz with 88% accuracy, whereas the best combination was EEG, pupil size and blinking rate with 91% (Hogervorst et al., 2014). Wilson collected data from pilots with ECG, EDA, EEG, EOG and EMG; and results suggested that amplitude in alpha and delta frequency bands in EEG correlated with the difficulty of the flight scenario, and heart rate measure provided more precise information compared to heart rate variability (Wilson, 2002).

The main reason for using different measurement methods simultaneously is their divergence in their sensitivity regarding the cause of mental workload. For example, EEG is good at discriminating dual tasks and single tasks, but weaker at discriminating between two single tasks, whereas heart rate variability is better at single task change detection, but fail at detecting difference between dual tasks and single tasks; according to a study with multiple metrics which scanned 150 participants (Matthews et al., 2015).

The classical Stroop task consists of color words which are colored either the same as their meaning or with a different ink, and therefore, a conflict occurs during trials with words that are colored with different inks, which is dubbed as the Stroop interference (Pessoa, 2013). In the Stroop task, high workload results in longer reaction times, and Stroop interference is preserved (Chen, 2003). On the other hand, when the meaning of the word matches the ink color, participants respond faster and this is called Stroop facilitation (Lovett, 2005). These tasks have various uses in both psychological research and clinical studies, for example, the virtual reality version of Stroop task is commonly used in assessing neurological capabilities of patients with brain injury (Henry et al., 2012; Parsons et al., 2011).

The n-back task is a working memory task with audio, alphabetical and visual grid variants. Depending on which variant is used the memory load either falls heavily on the visuospatial sketchpad or the phonological loop (Shallice & Cooper, 2015). Because it relies heavily on working memory, the n-back task is frequently used in mental workload studies (Parasuraman & Rizzo, 2009). The “n” stands for the order of previous stimuli: 1-back means comparing the current item with the previous stimulus, 2-back means comparing it with the item that was shown before the previous stimulus, and it goes on for any number that stands for n, except for 0-back which consists of comparing the presented stimulus with an item that was indicated at the start of the trial. Task difficulty increases as n increases, and therefore, the literature predominantly involves tasks up to 2-back or 3-back, since too difficult trials might cause loss of motivation among participants (Brouwer et al., 2014).

Sternberg Item Recognition task is another method for evaluating workload in working memory. In this task, a stimulus set is shown to participants, which is followed by probe trials that either contain items from the set or not, and the participant is instructed to respond for items which were in the stimulus set. Workload is shifted by increasing or decreasing the number of items. A previous study (Maurer et al., 2014) scanned 24 subjects with a 64-channel EEG as they performed the Sternberg Item Recognition task with two and four symbol trials. The results suggested that both alpha and theta rhythms in the frontal midline are correlated with workload in working memory.

Psychological tasks can also be used together as a battery. For example, the Multi-Attribute Task Battery II (MATB-II) developed by NASA (Santiago-Espada et al., 2011), features four tasks that assess mental workload, and also includes the subjective workload rating NASA-TLX. These four tasks are as follows: System monitoring task consists of responding every time a light goes on and off, and tracking four scales in order to respond each time one moves away from the middle. In the Tracking task, participants keep a moving target inside a box by joystick movements. The Communications task involves listening to the commands on the radio when the call sign of the simulation aircraft is announced, and then tuning into the frequency as ordered. The Resource Management task is pumping fuel from supply tanks into the aircraft's main tanks while keeping the amount of fuel inside the tanks within thresholds. NASA-TLX (Hart & Staveland, 1988) is filled by the participant and has 6 different ratings, namely mental demand, physical demand, temporal demand, performance, effort, frustration; on a scale of 1 to 10. NASA-TLX is typically administered after the completion of the main task.

Another study that featured NASA-TLX (Wetherell & Carter, 2014) investigated whether multitasking increased mental workload. Heart rate and blood pressure were measured with a cuff as twenty participants completed the multitasking framework that consisted of eight everyday tasks focusing on psychomotor, attentional, memory and perceptual abilities. The results showed that multitasking induced stress and increased mental workload. There are other subjective assessments as well. Subjective Workload Assessment Technique (SWAT) consists of judgments regarding Time Load, Psychological Stress Load and Mental Effort Load, and judgments are made on the scale of 0 to 100 (Reid & Nygren, 1988). Workload Profile separates workload dimensions as processing units which are rated on a scale of 1 to 10, and these dimensions are perceptual/central, spatial, verbal, visual, and auditory processing, along with dimensions of response selection, execution, manual output, speech output (Tsang & Velazquez, 1996).

Functional near-infrared spectroscopy (fNIRS) is a viable method to measure mental workload without interrupting the action (Boyer et al., 2015). Tasks with higher complexity have more demands placed on working memory, which has limited capacity and depends on PFC (Morrison, 2005). A previous study (Causse et al., 2017) tested 26 pilots in easy and difficult flight simulations under fNIRS recording. Two months later, the same participants were studied with working memory tasks, also with fNIRS to control whether findings in the flight simulation were an indicator of increased mental workload. In both experiments, difficult tasks resulted in more activation in the prefrontal cortex, specifically in the dorsolateral area, and thus fNIRS was shown as a reliable measure for cognitive load. This finding was corroborated by a study which found higher activation in the right PFC during multitasking, in the form of performing a grasping task and mental arithmetic concurrently (Mandrick et al., 2013).

In another fNIRS study, n-back task was used in all conditions between 0 and 3 (Herff et al., 2014). An 8-channel fNIRS device was employed to classify workload with accuracy rates between 72 – 81% against relaxed state for 1-back, 2-back and 3-back. In addition, successful discrimination between 1-back and 3-back trials were obtained with 78% accuracy. In light of these findings, authors asserted that fNIRS is a robust device for the evaluation of mental workload.

Electroencephalography (EEG) and fNIRS were used together on pilots in a flight simulation (Dehais et al., 2018) and the experiments consisted of trials with light and heavy air traffic and the pilots were required to respond to an auditory stimulus during flight. The results showed that the pilots made more response errors and also missed out some auditory signals under heavy workload. Moreover, these two devices provided better accuracy for evaluating mental workload when they are combined, in comparison to using a single modality. Another study on assessing mental workload with EEG suggested that the measurement might be frequency-specific, and showed dissociations in the alpha band frequency during tasks with higher load (Fink et al., 2005).

The ERP literature suggests that increase in mental workload results in smaller P300 values in the parietal region (Brouwer et al., 2012; Gajewski & Falkenstein, 2014) and smaller N100 values in the frontal and central areas (Allison & Polich, 2008). Late positive potential around visual cortex is regarded as a sign of increase in arousal (Hajcak et al., 2010; Schupp et al., 2006) whereas a more recent study (Brown et al., 2012) suggests that this late positive potential is due to a global inhibition which occurs in order to make way for processing stimulus in a more selective way. Late components of ERP might be a result of short-term memory activation, decision making in Go/No-Go tasks, and conflict interference in Simon and Flanker tasks (Danker et al., 2008; Falkenstein et al., 1995; Mecklinger, 2000; Olichney et al., 2000; Scrivano & Kieffaber, 2021; H. Yang et al., 2019). Parietal late positive components are associated with episodic recollection, memory retrieval, and recognition of previously encountered stimuli (Bencze et al., 2022; Dimsdale-Zucker et al., 2022). N400 findings in ERP are usually associated with semantic meaning (Proverbio, 2022) and response conflict (Larson et al., 2014); however, studies also detected prefrontal N400 when participants saw non-target stimuli, frontoparietal N400 when exposed to incongruent stimuli, and midline N200 and N400 in response selection uncertainty and rejection of false stimuli (Dimsdale-Zucker et al., 2022; Gajewski & Falkenstein, 2014; Proverbio & Zani, 2022) and stopping the action to respond (Hervault et al., 2022).

Measurement of change in electric potentials created by cardiac activity is called electrocardiography (ECG, however, in some resources the abbreviation is EKG because of the original German word). The number of electrodes differ among devices between a single electrode for obtaining data of heart rate and heart rate variability to 12-electrode settings that provide detailed clinical information regarding any shifts in the cardiac axis, and problems in cardiac muscles. In ECG, heartbeat waves labeled P, Q, R, S, T are analyzed for their orientation, amplitude and shape. Measurements for heart rate and heart rate variability are obtained from ECG data, and both can be used to assess mental workload (Pendleton et al., 2016).

Heart rate is one of the measurements that can be obtained from ECG, and rise of heart rate is among the indicators for high mental workload, which is thought to stem from the increase in heart rate during sustained attention (Reynolds et al., 2013). The calculation of heart rate from ECG is done by measuring the distance in time between the peaks of two consecutive R waves. The R wave is preferred because it shows the contraction of the left ventricle, and therefore the biggest and most distinctive wave, which is always present and can be measured easily even with devices with low sensitivity. Similarly, respiration rate and body temperature increase in tasks with high mental workload, and this effect is independent of physical difficulty of the task (Novak et al., 2011).

Heart rate variability (HRV) is another measure of mental workload (Croizet et al., 2004), and according to a meta-analysis (Hughes et al., 2019) it gives better information if workload is increased by making tasks longer to finish whereas less successful in showing the effects of change in event rate. The same meta-analysis showed that heart measures are more suitable to use in a laboratory setting. Another study tested twelve participants as they commandeered remote operating vehicles and demonstrated that lower prefrontal activation in fNIRS and HRV are sensitive methods of detecting high levels of mental workload (Durantin et al., 2014).

There are various glands in the human skin and when a person is under duress, such as being excited or tired, the activity of these glands increases and that results in a difference in electric potential on the skin. The change across time on this electric potential can be measured by placing two electrodes on the skin, which is called electrodermal activity. EDA is used in studies as an indicator of cognitive load, for example, Baldauf and colleagues (Baldauf et al., 2009) demonstrated that EDA measures obtained from two electrodes placed inside the left palm showed positive correlation with the amount of traffic in a driving simulator, which was also supported by the results of a subjective workload assessment technique (SWAT).

Measuring pupil diameter, called pupillometry, is also featured in mental workload research (Mandrick et al., 2016). In this study, participants were tested with a novel, arithmetic version of the n-back task and a positive correlation was found between task difficulty and pupil diameter, heart rate, and activation in the lateral PFC. On the other hand, phasic pupil response was negatively correlated with task difficulty. This work employed a remote eye tracker for pupillometry, namely the SMI RED500 (SensoMotoric Instruments GmbH, Germany). Another study (Marinescu et al., 2018) used the RED250 eye tracker from the same company along with a thermal camera (FLIR Systems, Wilsonville, OR, USA) to measure temperature from face recordings, and a chest strap (Zephyr BioHarness 3, Medtronic, Annapolis, MD, USA) to measure heart rate and respiration rate. The effect of task difficulty on these measurements was investigated as 10 participants shot target balls by their color as they fell down the screen. The results indicated that pupil diameter and face temperature were successful at estimating mental workload, which was also corroborated with subjective ratings of the participants on NASA-TLX.

Studies that feature physiological measurements to analyze mental workload in joint tasks are not very common. A study on twenty participants with a sustained attention task (Balconi, Gatti, et al., 2018) showed that negative feedback during cooperation resulted in subjective assessment of the performed task to be more difficult together with higher ratings of experienced mental workload. Anterior areas in the frontal cortex and the right DLPFC were associated with this negative effect, as well as an increase in skin conductance. Another study investigated changes in heart rate and skin conductance during competition over 16 same gender dyads (Vanutelli et al., 2018). The task was to detect target stimulus among four options, which were displayed for 500 ms with 300 ms inter stimulus interval. Feedback was given after each trial for 5000 ms, followed by a rest period of another 5000 ms. However, the feedback was artificial and participants were given fake very positive feedback to test the effects of reinforcement. Response times were lower after receiving positive feedback, and skin conductance increased. Synchronization was detected in both heart rate and skin conductance levels within the dyad, which also increased after positive reinforcement. Identical results were detected in a previous work on 12 dyads who were cooperating on the same task, instead of competing (Vanutelli et al., 2017). This suggests that physiological synchronization and the effect of positive feedback is similar for different joint action types.

In summary, mental workload measurement is associated with PFC (Foy et al., 2016), more specifically lateral PFC (Mandrick et al., 2016; Pessoa, 2013), right hemisphere PFC (Mandrick et al., 2013), dorsolateral PFC (Causse et al., 2017), lower PFC (Durantin et al., 2014). Another study (Helton et al., 2010) corroborated the findings regarding right lateralization (Mandrick et al., 2013), but only for simple vigilance tasks, and reported bilateral activation in difficult vigilance tasks, even though this could be specific to vigilance.

In EEG recordings, alpha (Maurer et al., 2014) and theta frequency in the frontal cortex (Toppi et al., 2016) are frequently reported as indicators for mental workload. This was further supported for both alpha and theta frequencies by a study on 20 participants with auditory and visual tasks (Käthner et al., 2014). At frontopolar electrodes, both alpha and theta powers reportedly decreased with increased workload in a driving simulator with auditory n-back task (He et al., 2019). Another study with a single frontal polar electrode did not find a significant effect of visual n-back task with 0- to 3-back levels on any of the EEG bands (Maimon et al., 2020). A 2012 study (Palomäki et al., 2012) focused on 4 - 35 Hz oscillations during the n-back task between 0- to 3-back found that 4 - 8 Hz power increased around 2200 ms after onset of stimulus across the cortex, whereas 8 - 25 Hz power decreased after 100 ms of stimulus.

Power spectrum analysis on EEG data suggests that the increase in theta band across the cerebral cortex is associated with high mental workload (Borghini et al., 2014) and mental fatigue (Lal & Craig, 2001) in the literature. Midline theta power increase is regarded as the most important sign for working memory load (Berka et al., 2007), parietal theta increase is associated with high task demand (Fairclough et al., 2005) and occipital theta power increase is linked to high mental workload (Arico et al., 2015). Frontal theta power increase is seen as a strong indicator for high mental workload (Lei & Roetting, 2011), mental fatigue (Wascher et al., 2014), mental effort (Dasari et al., 2017), increased task difficulty (Smith et al., 2001), retention of working memory (Jensen & Tesche, 2002) and sustained attention (Doppelmayr et al., 2008). In alpha band, even though there are studies that associate a parietal decrease in alpha band with increased mental workload (Brouwer et al., 2012), there are also other studies that claim a general increase in the alpha band across the cerebral cortex is a sign of high mental effort (Dasari et al., 2017), mental fatigue (Boksem et al., 2005; Charbonnier et al., 2016; Pergher et al., 2019), drowsiness (Papadelis et al., 2006), retention of working memory (Schack & Klimesch, 2002) and higher demand of the task (Klimesch, 1999). Increase in other bands are also regarded as an indicator of high engagement with the task (Heger et al., 2010), attention and working memory (Jensen et al., 2007), mental fatigue (Boksem et al., 2005; Lal et al., 2003), drowsiness (Nguyen et al., 2017), and mental workload (Mühl et al., 2014). In addition, increase in both alpha and theta powers indicate a decrease in alertness (Otmani et al., 2005). A previous n-back study linked lower oscillatory activity in frontoparietal theta and alpha bands to a reduced efficiency in the task (Gajewski & Falkenstein, 2014). A recent study suggested that centroparietal increase of power in theta power correlates with focus of attention whereas delta and gamma power increase is a sign of mind wandering (Dias da Silva et al., 2022).

2.5. Behavioral Measures of Mental Workload

The behavioral measures in the n-back literature generally consist of reaction times and task accuracy. While reaction time is measured in the same way across the literature, task accuracy can be evaluated with many similar but not identical metrics with various calculations that include the number of correct responses, the number of missed trials, the number of incorrect responses to either a Go trial that required another response or a No-Go trial, the total number of trials, and the ratio of these measures.

Reaction time is defined as the duration between the presentation of the stimulus to the participant and the response given to the stimulus by the participant. In the related literature, reaction times increase with higher mental workload. A previous study tested 25 undergraduate students with an n-back task consisting of four levels under 14 channel EEG recording and reported that the increase in n-back levels positively correlated with an increase in reaction times alongside increased frontal and central theta power in EEG, and NASA-TLX reports of the participants (Aksu et al., 2023). Another study which featured an n-back task with 1-back, 2-back, and 3-back levels under EEG and fMRI recording reported that the reaction times increased as the n-back level increased (Yoshiiwa et al., 2022).

A missed trial is a Go trial in which the participant fails to respond to the stimulus within the allocated duration. This can also be referred to as a “false negative” or an “omission”, since there is no response when there should be one (Longo, 2015).

A wrong response is a No-Go trial that the participant mistakes for a Go trial and gives a response. Sometimes, this is called a “false positive” or a “false alarm”, because there is a response even though there should not be one (Haatveit et al., 2010).

Both the missed trial and the wrong response are measures of task accuracy. In the related literature, task accuracy decreases with higher mental workload. In other words, participants make more errors, of both types, when the task becomes more difficult. For example, a previous study covering 1-back, 2-back, and 3-back levels while participants were under fNIRS recording reported that the number of wrong responses positively correlated with the increase in the n-back level (Herff et al., 2014). Another study reported that the number of missed trials increased as task difficulty increased in two different n-back tasks and an operation span task (Chooi & Logie, 2020). An operation span task is a working memory paradigm in which participants are requested to recite back all the items that were presented to them, in the same order.

Another behavioral measure suggested for working memory is d prime (d'), which is the Z transform of Hit Rate minus the Z transform of False Alarm Rate (Macmillan & Creelman, 1990). Hit Rate is the proportion of correct responses to correct responses and misses, and False Alarm Rate is the proportion of false responses in No-Go trials to false responses and correct no responses (Haatveit et al., 2010). As task accuracy increases, d' score increases as well; therefore, it negatively correlates with task difficulty. For the n-back task, it decreases when the n-back level increases.

D prime is featured in several studies as a sensitivity index for the evaluation of task accuracy of the participants. A transcranial stimulation study reported that participants had lower d' scores during the 3-back condition in comparison to the 2-back condition for all three experiment groups. The featured n-back task consisted of letters, and participants were tested under different transcranial stimulation methods. Their EEG findings showed that transcranial stimulation has a different effect on active and inactive cortical circuits (Hill et al., 2019). Another study employed an auditory n-back task either with or without background noise, and reported that the d' scores were higher for 1-back than 2-back in both conditions. They also reported an increase in frontal theta power as the n-back level increased (Hjortkjær et al., 2020). A recent study investigated the effect of training on working memory with fMRI, and found that the participants had lower 2-back d' scores than 1-back when they started the experiment but after six weeks of training, they had similar d' scores for 1-back and 2-back (Finc et al., 2020).

Depending on the procedure they use in their study, researchers might prefer other metrics of reporting task accuracy as well. For example, a recent study investigated the effect of training on several working memory tasks, and one of those tasks was the n-back task. In their task, the number of trials were not the same for every participant but instead, it depended on their speed and success. Therefore, to control for different number of trials between participants, they used the ratio of correct responses to the sum of correct responses, missed Go trials, and false responses in No-Go trials (Pahor et al., 2022). Another study only reported hit rate (the ratio of correct responses to total number of trials) to evaluate task accuracy for the n-back task as 21 participants were tested with a memory task about remembering visual stimuli either with or without an additional n-back task. Their results showed that DLPFC activation in fNIRS increases with the n-back task which in turn increased performance in the second visual memory task (Kimura & Matsuura, 2023).

2.6. Neuroimaging Techniques and Hyperscanning

Development of functional neuroimaging techniques made it possible for researchers to investigate which brain areas are more active during a cognitive process, and this improved our knowledge regarding human brain and human cognition (Bermudez, 2014). However, cognitive mechanisms underlying joint action are still under research. There is an array of different possible mechanisms (Obhi & Sebanz, 2011) and several methods to measure which regions of the brain are active during social interactions (Hari et al., 2015). Namely, these methods are electroencephalography (EEG), functional magnetic resonance imaging (fMRI), magnetoencephalography (MEG), positron emission tomography (PET), and functional near-infrared spectroscopy (fNIRS). It is important to note that every technique has its strengths and weaknesses, so applying multiple techniques at once, if possible, might yield more reliable and detailed data (Sejnowski & Churchland, 1989). Data obtained from neuroimaging measurements are analyzed for activity and connectivity amongst brain regions with further mathematical applications such as graph theory (van den Heuvel & Sporns, 2013).

Hyperscanning is the method of using neuroimaging techniques to obtain data from two or more participants simultaneously (Astolfi, 2014). It is an important method for the study of coherence between neural measures, which is an indication of integration (Varela et al., 2001). In the literature, various names have been used to refer to this finding, such as brain-to-brain synchrony (Dikker et al., 2017; Hari et al., 2013; Kinreich et al., 2017), neural phase synchronization (Fries, 2005; Schoffelen et al., 2005; Womelsdorf et al., 2007), inter-brain coherence (Baker et al., 2016; Balconi & Angioletti, 2023), neural coupling (Bilek et al., 2015; Hasson et al., 2012) among others. Previously, EEG-hyperscanning was the preferred method (Balconi & Vanutelli, 2017) which was used in studies that investigated neural mechanisms underlying cooperation during tasks such as the Prisoner’s Dilemma (Astolfi et al., 2011).

Functional MRI can also be used in hyperscanning studies (King-Casas et al., 2005) but it is preferred less frequently despite its high spatial resolution and precise localization of activation, because of the noise of the device hindering verbal communication (Koike et al., 2015). Even if the scanner noise is overcome with noise canceling headphones and fiber optic microphones (Spiegelhalder et al., 2014), the size of two fMRI scanners in a room alone is a difficulty in the way of setting up a proper environment for social interactions. Similarly, a study implemented MEG alongside EEG for hyperscanning on five pairs who were located almost a hundred miles apart, as they communicated via magnetic-compatible microphones and earphones as they counted to 30 by taking turns (Ahn et al., 2018), and the results indicated increased gamma oscillations and phase synchronization during verbal interaction. Overall, fMRI and MEG might provide detailed information, but in contrast to them, measurements by EEG or fNIRS can be conducted during activities in a more natural setting (Koike et al., 2015).

EEG is a common technique which allows the measurement of electrical activity in the cortex through the scalp, and provides data on change across time and location of activity, as well as the frequency of electric potential oscillations (Cohen, 2014). EEG has good temporal resolution but spatial data can be noisy due to electric potentials caused by movements of eye or face muscles, and sweating (Keil, 2013). This noise can be filtered with the help of other electrography techniques, such as electromyography (EMG), electrooculography (EOG) and EDA, or by applying Fourier transformations (Luck, 2014).

An important advantage of EEG is that it allows for a small amount of movement when it is placed with a headset, and participants can be tested sitting side by side in a room, both of which are not possible with fMRI or MEG. For example, in (Tsai et al., 2006), 26 participants in dyads were tested with a Go/No-Go task specifically developed for this study. The analysis of both behavioral and EEG data indicated that participants in the dyad represented each other mentally and thus tried to anticipate what the other person will do next. This finding supported claims from other researchers regarding the shared mental representations during joint action (Obhi & Sebanz, 2011; Sebanz et al., 2003, 2006).

Another EEG-hyperscanning study (Dumas et al., 2010) studied 11 dyads who imitated each other. The EEG system consisted of one amplifier (BrainProducts, Germany) and two headsets with 32 channels placed as the 10/20 system, and obtained data on four frequency bands: theta (4 – 7 Hz), alpha-mu (8 – 12 Hz), beta (13 – 30 Hz), and gamma (31 – 48 Hz). The experiment had two blocks of 10 minutes. The results indicated synchronization in the right centroparietal regions in alpha band, which is associated with the mirror neuron system, as well as in the central and right parieto-occipital regions in the beta band and over the centroparietal and parieto-occipital regions in the gamma band which are attested to motor movement during the imitation (Please see Figure 5).

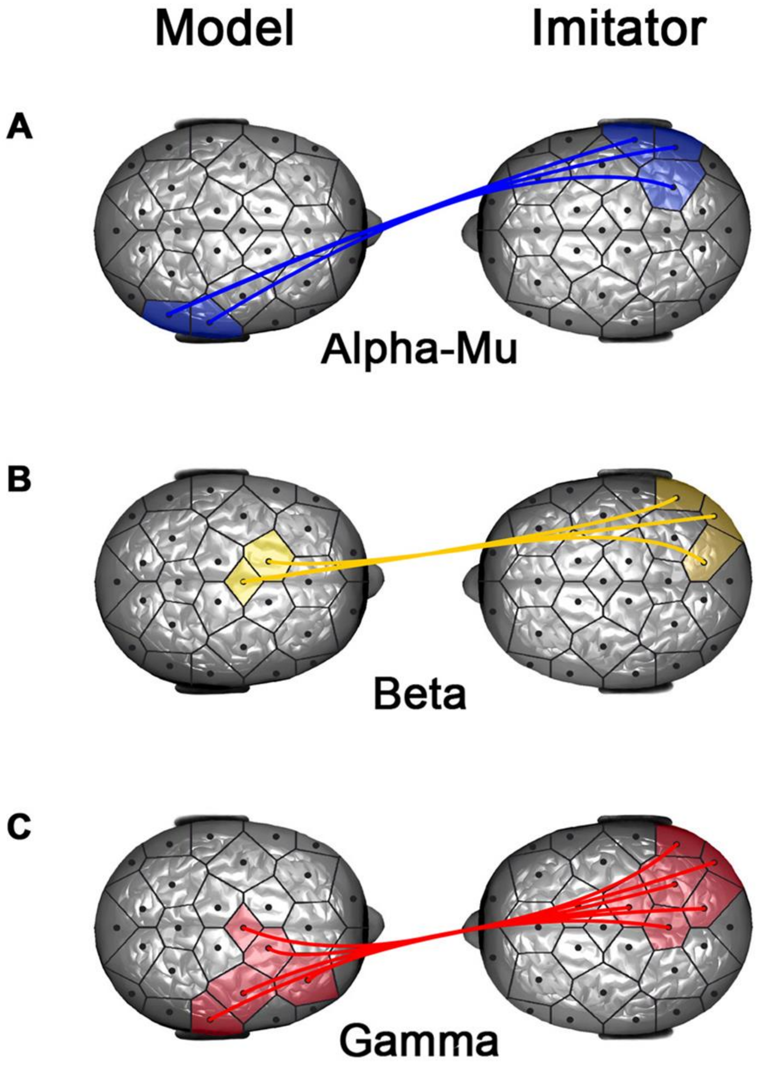


Figure 5: Areas that showed synchronization in an imitation experiment (Dumas et al., 2010, p. 6).

A 2016 study applied EEG-hyperscanning on 6 dyads of captains and first officers inside a flight simulator. Takeoff and landing phases of the flights were regarded as highly cooperative tasks whereas the cruise phase was regarded as a non-cooperative task. Subjective ratings in NASA-TLX, along with heart rate and blink rate measures, indicated that mental workload was higher during landing in comparison to cruise phase. Inter-brain connectivity was detected between frontal and parietal cortex during cooperative takeoff and landing phases, and there was no connectivity during the cruise phase (Toppi et al., 2016).

Since EEG devices are portable and silent, they allow for multiple data collection simultaneously without interrupting the natural flow of the interaction. An EEG-hyperscanning study investigated brain-to-brain synchrony in the classroom during lectures (Dikker et al., 2017). Data was collected from the teacher and all twelve students in the class simultaneously. Eleven 50-minutes long lectures were assessed over three months. The results showed that brain-to-brain synchrony predicted student's engagement to class and can be used as an indicator for joint attention.

Event-Related Potentials (ERP) are specific electrophysiological reactions in cortex to certain events, which is obtained by analyzing EEG recordings with temporal markings (Sur & Sinha, 2009). The fine spatial resolution allows for research even in milliseconds (Pessoa, 2013). Time, location and the amplitude of ERP waves, either positive or negative, are used to identify certain cognitive processes (Cohen, 2014). For example, participants in the competitive condition showed higher amplitudes in both P3 and N1 waves when they were tested with the Eriksen Flanker task (Eriksen & Eriksen, 1974) and images that contain painful or non-painful situations (F. Cui et al., 2016). The flanker task consists of a target stimulus and one or more flanker stimuli presented as a distraction. By assessing different target stimuli, it is possible to employ a joint flanker task. In the joint flanker task, the flanker effect is stronger than the individual version, and according to a study that consisted of four experiments with up to 57 participants (Atmaca et al., 2011), this is attributed to the use of attentional resources by shared representations between co-actors, and these shared representations only occur if participants see the other person in the dyad as acting intentionally. Another study tested 80 participants with the joint Simon task and the joint flanker task (Dittrich et al., 2017) and the results showed that if the co-actor is not visible, the joint Simon effect is still observed whereas the joint flanker effect is lost. Therefore, the setting of the experiment environment is an important factor for the emergence of social effects.

Another study assessed 17 participants with a 3-hour long visual attention task, and used EOG and EEG devices to obtain data (Boksem et al., 2005). An ERP analysis was conducted on N1 and P1, which mark attention early on, and N2b which indicates further procession of the item in focus. The findings revealed that mental fatigue results in impaired goal-directed attention and the participants' behavior indicated a stimulus-driven performance as they became more tired.

Functional Magnetic Resonance Imaging (fMRI) provides detailed spatial information regarding neural activity through the Blood Oxygen Level Dependent (BOLD) measure (Logothetis, 2008), although the temporal resolution is low (Siegel et al., 2012). However, participants have very limited movement, and they are away from other participants so the cooperation takes place offline. Some studies showed video recordings of the collaborator or the competitor in order to overcome this constraint (Decety et al., 2004).

Because of its advantage in spatial resolution, fMRI is still a popular method of neuroimaging. A functional Magnetic Resonance Imaging study (Grèzes et al., 2003) showed that when an individual witnesses another person carrying out an action, that individual's representation system for the same action is also activated, which also supports the shared representations claim (Loehr et al., 2013). A previous study(Sebanz & Frith, 2004) revealed that the ventral premotor cortex is active during joint action tasks, which points to the ability of predicting the other person's behavior with whom the individual is sharing the task. For individual tasks, the constraints of fMRI become less important, and a previous study revealed that behavioral data and fMRI recordings matched very well for simulating an individual's decision-making patterns in the stock market (Ogawa et al., 2014).

Another study which used fMRI featured a Stroop task with only red and green, 1500 ms stimulus duration and 3000 ms break between blocks of naming either words or colors, and participants responded with left or right mouse clicks. The results suggested that left middle frontal gyrus and superior frontal gyrus are also associated with the Stroop task (Egner & Hirsch, 2005). According to the other studies in the literature, neurocircuitry regarding the Stroop task consists of DLPFC for selecting relevant information, and posterior parietal cortex for representation of stimulus-response mappings (Bush et al., 1998; Van Veen & Carter, 2005).

MEG records the brain's magnetic fields and gives the most detailed temporal and spatial information, but it is a very expensive device and requires a special room (Lopes da Silva, 2013), therefore it is quite difficult to use in research regarding social interactions. Positron emission tomography (PET) provides information regarding which brain regions are active during an action via how cerebral blood flow changes in that time period (Decety et al., 1994), but it requires injection of radioactively labeled water on top of the radiation given by the tomography machine, which prevents it from being a primary choice in experiments. In a previous study with PET scan (Harrison et al., 2005), the Stroop task was used. The task consisted of four colors: blue, red, green, yellow. Stimulus was shown for 1300 ms with 350 ms breaks between stimuli. The order of the conditions was six congruent following six incongruent trials. The results suggested that a cingulofrontal network involving ACC is responsible for responding to the relevant aspect of the task, and another network including DLPFC was more active in inhibiting the irrelevant response.

Functional near-infrared spectroscopy (fNIRS) brings together advantages of other neuroimaging techniques along with the advantages portability and ability to conduct experiments "in situ", meaning that participants will be recorded in "mobile pop-up labs" (Dieffenbach et al., 2021) or in a natural setting as they are doing things in real life, such as walking indoors or outdoors (Atsumori, 2010; McKendrick et al., 2017) and driving (Pinti et al., 2018). This would prevent the possible effect of being in a closed, controlled environment on the outcome of the experiment, and possibility of the activation in the prefrontal cortex due to norm compliance during artificial, rule-based situations being misidentified as a neural finding specific to the task being tested (Buckholtz & Marois, 2012). It provides data concurrently with the task (Gateau et al., 2015) and has very good spatial resolution, as well as good temporal resolution that it is considered as a suitable medium for a brain-computer interface (Aranyi et al., 2016).

Functional near-infrared spectroscopy utilizes near-infrared light to measure the ratio of oxygenated hemoglobin to deoxygenated hemoglobin in the cortex, and this shows metabolic changes caused by neural activity (Gentili et al., 2013). Also, signal-to-noise ratio can be calculated by changes in the hemoglobin concentration and optical path length (Funane et al., 2009). In order to validate the efficiency of this method in detecting cortical activity, a 2013 study (Sato et al., 2013) compared BOLD signals from fMRI to oxygenated hemoglobin data from fNIRS and also compared fNIRS data to measurements from the skin of the forehead. Results from 27 participants showed that fNIRS data is reliable in detecting specific activity in the cortex and does not stem from superficial measurements in the skin.

Since hair causes problems in the distribution of near-infrared light, best data is obtained through hairless areas, mainly the front of the head (Dieffenbach et al., 2021). Therefore, fNIRS is used in a wide range of studies to assess the activity of regions in the prefrontal cortex (PFC) (Atsumori et al., 2009). PFC is very important for keeping and manipulating information, and has various subparts with different functions such as medial prefrontal cortex (Pessoa, 2013). PFC is also involved in other cognitive processes, such as emotional reaction to music (Bigliassi et al., 2015), marketing applications (Çakir et al., 2018), rational thought (Goel, 2005), and reasoning by comparison or making analogy, solving problems, induction and deduction (Shallice & Cooper, 2011).

There are numerous examples of research using fNIRS. In a study, fifteen participants were awarded real money according to their success during a stock market simulation to motivate them into making decisions as if the situation was real. It was found that medial prefrontal cortex and orbitofrontal cortex are highly active during decision making (Shimokawa et al., 2009). OFC is regarded as the region for the integration of emotional and cognitive processes (Coricelli et al., 2005), especially for evaluating possible negative consequences and regret (Camille et al., 2004).

In another study (Causse et al., 2017), 26 pilots were tested in easy and difficult flight simulations under fNIRS recording. Two months later, the same participants were studied with working memory tasks and fNIRS measuring to control whether findings in the flight simulation were an indicator of increased mental workload. In both experiments, difficult tasks resulted in more activation in the prefrontal cortex, specifically in the dorsolateral area, and thus fNIRS is shown as a reliable measure for mental workload. Another study (McKendrick et al., 2014) showed that when ten participants were tested with working memory tasks under fNIRS recording, training increased hemodynamic response in left dorsolateral prefrontal cortex (DLPFC) and right ventrolateral prefrontal cortex. For studying verbal communication, fNIRS is as effective as fMRI, as fNIRS recordings of listeners' and speakers were shown to have a correlation (Y. Liu et al., 2017) which was also compared with fMRI data.

Recently, fNIRS began to replace EEG as the common method for hyperscanning since it provides better spatial resolution and has better ecological validity than fMRI while providing adequate temporal resolution (Pan et al., 2017; Reindl et al., 2018). Still, a combination of fNIRS and EEG brings together advantages of both techniques. A recent study that combined these two modalities (Fronda & Balconi, 2022) found that prosocial activity, gift-giving in the context of this study, resulted in an increase in frontal delta and theta band coherence as well as DLPFC HbO in a simple memory task. The authors argued that this increase of coherence facilitates the co-representation of the shared task.

When conducting hyperscanning with fNIRS, it is possible to either use two different fNIRS machines or use one machine with two headsets (X. Cui et al., 2012; T. Liu et al., 2017; Pan et al., 2017; Reindl et al., 2018). Usually, a single fNIRS device is connected to separate headsets (which contain optodes that obtain the data) that are placed on different people because this method facilitates synchronization. This method facilitates synchronization of the recording in comparison to using multiple fNIRS devices. Afterwards, the data is cleaned from artifacts (Molavi & Dumont, 2012) and then analyzed for interpersonal brain connectivity with methods such as Granger causality (Seth et al., 2015) and wavelet transform coherence (X. Cui et al., 2012; Nozawa et al., 2016).

Wavelet transform coherence (WTC) measures interpersonal neural synchronization by calculating the amplitude of the complex coherence value of analogous fNIRS channels between participants. In the study which introduced this method (X. Cui et al., 2012), the differences between individual action, cooperation and competition were investigated with a simple temporal task. Participants were expected to press a button right after seeing a go signal on the screen, and in the cooperative case they were instructed that they will win if their reaction times are close, in the competitive case they were told that whoever presses first wins, and in the individual task each participant did the task alone. All tasks were performed during fNIRS recording with a single fNIRS instrument used for both participants via two headsets. Their findings revealed an increase in signal coherence located at participants' right hemisphere superior prefrontal cortex during cooperation, in comparison to competition and individual action.

Phase synchronization and neuronal coherence is linked to neuronal communication and interaction (Fries, 2005; Schoffelen et al., 2005; Womelsdorf et al., 2007), which explains shorter reaction times and better task performance. A recent study investigating the effect of close social presence during simple arithmetic tasks found an increase in coherence around the reaction times located at the left frontal cortex (Miura & Noguchi, 2022). Another study found that compared to resting-state, an increase in WTC values for both HbO and HbR was detected at bilateral DLPFC while playing Rock-Paper-Scissors (Kayhan et al., 2022).

The literature suggests that brain synchronization is stronger between people who have emotional or social bonds, such as parent-child dyads (Feldman, 2015; Lee et al., 2017; Reindl et al., 2018) and romantic couples (Kinreich et al., 2017; Pan et al., 2017). Hyperscanning with fNIRS revealed increased activation in DLPFC and FPC in parent-child cooperation compared to cooperating with strangers and parent-child competition (Kruppa et al., 2021; Reindl et al., 2018) and high inter-brain connectivity is associated with emotional synchrony and stronger bonding between parent and child (Lee et al., 2017). The same applies to romantic couples, interpersonal brain synchronization among them result in better cooperation as indicated with faster reaction times, reduced variability and better task performance when compared to dyads consisting of strangers (Pan et al., 2017).

Similarly, an EEG-hyperscanning study on 104 participants scanned either romantic couples or dyads of male and female participants, reported increased brain to brain synchrony at temporoparietal area of romantic couples at the gamma range, which was correlated with behavioral synchrony and only occurred during social interaction, not during the rest phase. The strangers did not display inter-brain synchrony but the level of neural synchronization was positively correlated with mutual gaze and positive feelings towards each other (Kinreich et al., 2017). In the event of failure during cooperation, the synchrony is lost and synergic activity breaks down (Balconi, Vanutelli, et al., 2018).

On the other hand, a recent study investigated human-robot interaction and found that even robots can affect coherence of neural measures among co-actors: When a robot joined a human-human dyad as a third co-actor, coherence in the right PFC decreased even though the level of coherence was still higher compared to the single human actor condition (Howell-Munson et al., 2022). In the same study, sharing the task with another human and/or a robot resulted in a decrease in workload measures in comparison to performing alone. Still, it is important to note that the effect of the robot decreased coherence whereas sharing the task with humans, especially familiar humans who trigger positive emotional responses, increased coherence.

A study featuring fNIRS scanned 31 dyads as they performed a task in which they named and described objects to each other, taking turns for speaking and listening every 15 seconds for a total of 6 minutes divided in two equal blocks (Hirsch et al., 2018). Optodes were placed on sides of the head instead of forehead and wavelet transform analysis was conducted on the obtained data with MATLAB (Mathworks, Natick, MA, USA) for the detection of inter-brain coherence. The results indicated dynamic coupling between Wernicke’s areas and superior temporal gyrus of participants during interaction.

Many computer games have multiplayer modes, which make people participate in the same action at once, through either collaboration or competition. These multiplayer games are used as experimental paradigms for understanding the mechanisms underlying joint action as they are highly motivating, commonly known and widely used (Gray, 2017). Humans tend to behave in a manner which is different from the ideal strategy and very difficult to predict, and investigation of such behavior might provide insight into human cognition (Sun, 2016).

Of course, multiplayer games are not limited to computers, board games and card games are also possible mediums for studying social interactions. For example, a recent study scanned 60 participants in three-person groups as they solved tangram puzzles, with one person watching as the other two solved the puzzle by interacting or all three solved independent puzzles on the same table (Fishburn et al., 2018). Participants conducted all task conditions for blocks of 2 minutes each, with 45 seconds of breaks in between. The fNIRS device had 18 optodes which were distributed on three participants equally. The results showed that neural activation was coordinated in interacting pairs, unlike solving the same puzzle independently. When a participant watched the other two solve the task, all of them had interpersonal neural coordination, but this was stronger among the interacting pair. The time course of neural activation for a participant in the pair could be estimated from the other participant in the pair, but this was not possible for observers or participants doing the same task independently. Their findings indicated inter-brain coupling in shared intentionality during social interactions.

In another study, fNIRS data was collected from eighteen participants who played Jenga (Hasbro) in pairs while sitting on a table facing each other (N. Liu et al., 2016). There were four different tasks: Building a tower together as high as possible, trying to trick the other into making a wrong move which would fall the tower, build separate towers side by side, and just discuss on a given topic. Each task was conducted for two blocks of one minute each, with rest periods of one minute in between. Optodes were placed on right PFC and right STS of participants, with 9 optodes for each area and simultaneous fNIRS recording was obtained on 10 Hz with the device of ETG-4000 Optical Topography System (Hitachi Medico Co., Tokyo, Japan). The results pointed towards inter-brain synchrony during cooperation and obstruction but not during parallel play or dialogue. The synchrony was detected at Brodmann Area 8, which is located at the middle and superior frontal gyrus. Only in the cooperative task, inter-brain synchrony also emerged in right dorsomedial PFC, which corresponds to Brodmann Area 9. However, their findings are in contrast to a previous study which applied fNIRS-hyperscanning on 10 dyads (Jiang et al., 2012) and found inter-brain synchronization on left inferior frontal cortex during dialogue if participants faced each other, but not if they stood back-to-back. The authors attributed this effect to the existence of nonverbal cues during face-to-face communication. A more recent study reported inter-brain synchronization on the same region when participants just made eye to eye contact (Hirsch et al., 2017), which is in line with this claim.

Similar to board games, card games are also used in the experiments, for example, researchers collected fNIRS data from participants during a poker game (Piva et al., 2017) and investigated the areas associated with competition. Participants sat across each other in twenty pairs and played a simple version of poker via computer screens. Each trial consisted of a 6 s decision phase and 5 s result screen. In a second set of trials, participants also played against a computer. Results revealed activation and inter-brain synchronization in a wide neural circuit specific to social interaction located at frontal and parietal regions, covering temporoparietal junction, fusiform gyrus, somatosensory cortex, DLPFC, and left subcentral area. Between participants, synchronization was located between DLPFC and supramarginal gyrus, also between angular gyrus and fusiform gyrus. For each participant, neural connectivity increased between angular gyrus and DLPFC. Another study that featured a simple card game recorded EEG data from four participants at the same time. A total of 20 subjects were studied in groups of 4 people and cooperated in pairs during the game. In order to avoid disrupting data collection, participants called the card they will play out loud instead of moving. The results indicated that anterior cingulate cortex (ACC) is the region for representing other people’s intentions (Babiloni, Cincotti, et al., 2007). Anterior cingulate cortex is a part of medial PFC and it is associated with processing of emotions (Vogt, 2005), for example, an fMRI study on 19 participants showed that higher activation in dorsal ACC is an indicator for the strength of feeling envy (Takahashi et al., 2009). It is highly connected with anterior insular cortex (AIC), which is a part of ventrolateral PFC and this connection is regarded as the neural circuitry for agency (Craig, 2009) and prediction (de Lange et al., 2018).

In the hyperscanning literature, Temporo-Parietal Junction is reported to show interbrain connectivity during cooperation, as well as possible networks connecting TPJ to PFC (Osaka et al., 2015), to Temporal Lobe (Czeszumski et al., 2022), to central and left-temporal regions (Kurihara et al., 2022), or to right supramarginal gyrus which is located in the parietal cortex (Heggli et al., 2021). Coherence is observed at the frontopolar and central alpha bands in motor synchronization whereas delta and theta bands showed coherence in the same region if the same dyad was in a cognitive synchronization task (Balconi & Angioletti, 2023). Another study reported increased coherence in theta and gamma bands during cooperation, but only theta band coherence correlated with a decrease in reaction times, which they assessed as coherence in theta band showing motor synchronization and coherence in gamma band showing shared intentions (Barraza et al., 2020). Interbrain connectivity during social situations has also been reported in right centroparietal oscillatory activity in alpha band and central oscillations in the theta band (Bolt & Loehr, 2021; Dumas et al., 2010; Moreau et al., 2022). During social engagement, interbrain connectivity was detected at low alpha (7–10 Hz) and beta (20–22 Hz) bands, which correlated with empathy and social closeness (Dikker et al., 2021).

Intrabrain frontal alpha synchronization is associated with top-down control (Benedek et al., 2011) and inhibition (Klimesch et al., 2007). Intrabrain coupling between theta and gamma oscillations are regarded as working memory activation (Chaieb et al., 2015; Lisman & Idiart, 1995; Vogel & Machizawa, 2004), even though a recent study argues that it is not specific to working memory and observed in attentional and perceptual processes as well (Papaioannou et al., 2022). A new study (Moreau et al., 2022) reported interbrain connectivity in the gamma band oscillations in addition to the theta band, and intrabrain coupling between gamma and theta frequencies. Both interbrain and intrabrain coherence were reported in frontocentral delta and theta frequencies for guitarists playing duets (Müller & Lindenberger, 2022).

2.7. Personality Traits

The personality traits of participants have been investigated in several studies in the literature. Most measures, including TIPI, use five traits which are called the “Big Five”: Extraversion, Agreeableness, Conscientiousness, Emotional Stability, Openness. Other questionnaires that feature Big Five are BFAS (Jach et al., 2020), BFI-10 (Rammstedt & John, 2007), NEO-FFI (Baumgartl et al., 2020; Wacker & Gatt, 2010), NEO PI-R (Stough et al., 2001), FFPI (Tops et al., 2006), and IPIP (Knyazev et al., 2019). The related literature considers all of these five traits to be linked to personal feeling of well-being

(Sandstrom & Dunn, 2014) and self-reports regarding a meaningful life (Oishi & Westgate, 2022).

Self-administered short versions of the Big Five such as TIPI and BFI-10 are regarded as a robust method of assessment for personality with high levels of reliability and validity (Rammstedt & John, 2007), including a retest after five years of first evaluation (Lang et al., 2011). Short measures like Mini-IPIP (Donnellan et al., 2006) and even single item measures are regarded as useful tools for psychological research (Fisher et al., 2016).

Participants with a high score in extraversion mean that they rated themselves to be more extroverted and enthusiastic, and less reserved and quiet. It is regarded as the most relevant Big Five dimension to social competence (Anderson & Kilduff, 2009). A previous study (Baumgartl et al., 2020) evaluated resting state EEG data with machine learning and predicted the extraversion of the participant with 60.6% accuracy. Another study reported an association between extraversion and delta/theta Pz – Fz EEG activity (Wacker & Gatt, 2010). Participants with low scores in extraversion report a higher sense of belonging in social interactions with weak ties, such as attending to the same class in the school (Sandstrom & Dunn, 2014). Additionally, self-reports regarding a happy life shows highest correlation with extraversion among the Big Five traits (Oishi & Westgate, 2022).

A high score in agreeableness mean that the participants rated themselves to be more sympathetic and warmer, and less critical and quarrelsome. An earlier study investigated the EEG correlates of the agreeableness trait of the participants during social interaction and found that activity in the theta frequency band around the temporo-parietal junction is important for the mediation of social stimulus and behavioral response, and the agreeableness score of the participant affects the strength of this mediation (Knyazev et al., 2019). Another study found a correlation between the agreeableness score of the participant and error related negativity in EEG data during the Flanker task (Tops et al., 2006).

Conscientiousness is higher for participants who rated themselves to be more dependable and self-disciplined, and less disorganized and careless. A previous study suggests a negative correlation between the conscientiousness score of participants and theta band activity in the frontal region during photic stimulation (Stough et al., 2001). Another study found a correlation with an effect size of $r = .30$ between the beta band power in resting state EEG and the conscientiousness score of the participant (Jach et al., 2020).

Participants with a high score in emotional stability mean that they rated themselves to be calmer and more emotionally stable, and less anxious and harder to be upset. Some studies call this trait Neuroticism. The theta band in the power spectrum analysis of resting state EEG data has been used to predict the emotional stability score of the participants with an effect size of $r = .20$ (Jach et al., 2020). Among the Big Five, it is reported as the trait that is best assessed by self-evaluation, whereas extraversion is assessed similarly either by the participant or people from other perspectives, such as friends (Vazire, 2010).

Openness, sometimes referred to as “Openness to New Experiences”, is a measure which is higher for people who rated themselves to be more complex and open to new experiences, and less conventional and uncreative. In EEG data, the openness scores of the participants are reported to positively correlate with theta band increase across all regions while they were subjected to photic stimulation (Stough et al., 2001). Other studies reported a link between the openness score of the participant and the effect of interaction with classmates on well-being (Sandstrom & Dunn, 2014) or self-reports regarding a psychologically rich life (Oishi & Westgate, 2022).

Several studies point to a relation between EEG measures and personality traits. One of those studies (Klados et al., 2020) recorded EEG data from 37 participants while watching short videos with emotional content, used brain networks and graph theoretical parameters with a feature selection algorithm and support vector machines; and accurately classified the participants on each trait of the Big Five: Extraversion (83.8%), Agreeableness (86.5%), Conscientiousness (83.8%), Emotional Stability (83.8%), Openness (73%). A previous study (Zhao et al., 2017) with emotional short video clips from various movies classified data from 43 participants with accuracy of 81.08% for extraversion, 86.11% for agreeableness, 80.56% for conscientiousness, 78.38% for emotional stability, 83.78% for openness. A similar study on predicting personality traits from EEG data (W. Li et al., 2020) reported accuracy levels of 82% for extraversion, 71% for agreeableness, 72% for conscientiousness, 86% for emotional stability, 71% for openness, from a cohort of 66 participants who watched 28 video clips that showed positive, neutral, or negative emotions.

2.8. Aim and Hypotheses

Proper understanding of the human mind requires understanding of the social dimension as well as the individual (Seemann, 2011) since acting in isolation is quite uncommon for humans (Vesper et al., 2017). Joint action is a domain in which motivational and cognitive elements interact in complicated ways that are yet to be well understood (Pacherie, 2011).

Previously (Sebanz et al., 2003), it was argued that people share mental representations when they collaborate on a joint task, and these representations increase mental workload. However, this is still under debate and the literature is divided on the subject. There are studies that support the shared mental representations hypothesis (Baus et al., 2014; Demiral et al., 2016; Liefooghe, 2016; W. Liu et al., 2019; Ruys & Aarts, 2010; Schmitz et al., 2018), and those who oppose it (Klempova & Liepelt, 2016; Saunders et al., 2019; Yamaguchi et al., 2019). As the knowledge regarding collective behavior accumulates, some researchers are even going as far as suggesting that task sharing groups by itself can be considered as an information processing system on their own (Goldstone & Gureckis, 2009; Theiner, 2018).

Furthermore, contents of these task co-representations are also under debate. It is suggested that task co-representations are formed to reflect which of the co-actors is responsible for that part of the task and when it is their turn (Wenke et al., 2011). However, the more common opinion is that task co-representations are about what each other is doing, supported by studies in which participants performed better in recalling items their co-actor were supposed to respond in comparison to trials neither of them were expected to follow, even if that was detrimental to recalling their own items (Eskenazi et al., 2013).

In my master's thesis (Usal, 2016), it was found that participants in the joint task conditions reproduced the duration of the task significantly shorter than the actual duration when compared to participants who did the same task alone. However, only reaction times and time reproduction ratios were analyzed since no physiological measurement was obtained. On the other hand, studies that investigated the mental workload usually focus on individual action and little information is available on mental workload during joint action. It is suggested that detecting and tracking other people's intentions, which is a part of joint action, utilizes attentional resources (Thompson & Parasuraman, 2012).

In the current study, the aim is to obtain data from both EEG-hyperscanning and fNIRS-hyperscanning methods, and analyze the effects of working memory load and social presence on cortical activation and connectivity, and whether personality traits of the participants modulate these effects. By applying tasks with increasing mental workload and measuring via several methods, current state of knowledge on the subject will be tested and improved. For example, it is not clear whether there is a ceiling effect on mental workload. If mental workload increases both by task difficulty and social setting, it might be overwhelming for the participants, and it is not possible to foresee how this will affect them. Their task performance might be impaired or they might stop co-representing to decrease mental workload. The aim of this dissertation is to explore such aspects in relation to empirical data obtained via a dual EEG/fNIRS hyperscanning setup.

The hypotheses of this study are:

(i) The increase in the n-back levels results in higher mental workload

(ii) The social presence affects the mental workload experienced by participants, and this effect depends on their degree of extraversion

(iii) Interbrain coherence increases when people perform the n-back task together in contrast to individual performance

Prior studies have identified the possible role of social presence on cognitive task performance mainly through behavioral measures (Richardson et al., 2012). Although the reported effects point to social facilitation effects, the precise nature of this facilitation and its neural underpinnings are not well understood. In an effort to address this gap, a hyperscanning study was conducted to assess if any interbrain connectivity occurred between the participants. Intrabrain coherence measures were evaluated to understand the neural dynamics during the n-back task and social presence. EEG and fNIRS devices were used together to benefit from the advantages of both devices for only the small cost of losing two frontopolar electrodes. The fNIRS technique provides detailed spatial information regarding the activity patterns in the prefrontal cortex whereas the EEG technique has much higher temporal resolution. A meta-analysis of n-back studies (Owen et al., 2005) investigated 24 articles and reported that the lateral prefrontal cortex and posterior parietal cortex show robust activity during the n-back task. Using EEG allowed us to obtain data from the parietal cortex, which we could not with our fNIRS devices due to hair, while recording fNIRS data to assess the prefrontal cortex with higher spatial resolution. It was also deemed beneficial to assess how these two different measures relate to each other and whether these two separate measures would show similar results or not.

CHAPTER 3

METHODOLOGY

3.1. The Participants

The necessary sample size was calculated using the G*Power analysis tool, version 3.1 (Faul et al., 2007, 2009). In a repeated measures design with two conditions, for an effect size of 0.505 and $p < .05$, minimum sample size is suggested as 56 participants. In the study, a total of 62 participants (34 males, mean age: 25.4, *SD*: 4.1) were tested with a dual version of the n-back task in 31 same gender dyads. The experiments were conducted at COGS Lab, located at the building of Graduate School of Informatics in Middle East Technical University main campus. Participants were recruited via email, online announcement and face-to-face invitations across campus. No gender or age specifications were set for the participants except that they will be required to be adults. Most participants were undergraduate or graduate students from Middle East Technical University.

Participants were tested in same gender dyads to avoid any effect of gender. According to a 2016 study which studied 111 dyads with fNIRS-hyperscanning (Baker et al., 2016), only dyads which consisted of same gender participants showed inter-brain coherence during cooperation, and this coherence was positively correlated with task performance. The task was to press a button simultaneously. Moreover, coherence was also found in different parts of the cortex; which was located at the right inferior PFC for dyads consisting of males and at the right temporal cortex for dyads consisting of females. In the experiments, participants were positioned in opposing tables and they could see each other. However, their findings were in contrast with a previous study on 45 dyads which also featured the same simultaneous button-press task and fNIRS-hyperscanning (Cheng et al., 2015) as it reported that mixed gender dyads showed significant inter-brain coherence in OFC and left DLPFC which was correlated with successful task performance, whereas same gender dyads did not show any specific localization. Still, both studies reported that task performance was better in male-male dyads and mixed gender dyads in comparison to female-female dyads, which suggests that this difference in inter-brain coherence was not related to any difference in task performance. An earlier fMRI study (Yamasue et al., 2008) found that female participants had higher cortical thickness in anteromedial PFC and IFG, which take part in mirror neuron system and cooperation, and they interpreted this result in support of the theory that cooperativeness has a genetic background on the X chromosome (Skuse, 2005). Overall, it seems that the effect of gender in dyads needs to be studied further but, same gender dyads were preferred in this study since Baker and colleagues (Baker et al., 2016) had a larger sample size.

3.2. The Procedure

In the featured n-back task, letters appeared on a 3x3 grid (Please see Figure 6), and participants either responded to the letters with the “z” button or to the place of the letter on the grid with the “3” button on the numpad. The n-back task consisted of 0, 1, 2, and 3-back blocks, which is the common methodology in the literature (Owen et al., 2005). All blocks had 30 trials each, ten trials were Go trials for participant 1, ten separate trials were Go trials for participant 2, and 10 trials were No-Go trials for both participants. In each trial, the stimulus was shown for 500 ms, which was followed by a 2000 ms inter-stimulus interval. This resulted in 75 seconds long n-back blocks, and there were 10 seconds of rest between each block. To avoid any effect of learning, three separate versions of the task were prepared in which the order of the letters and their places were different. Version order was counterbalanced between dyads. The featured n-back task was prepared with OpenSesame experiment builder (Mathôt et al., 2012).

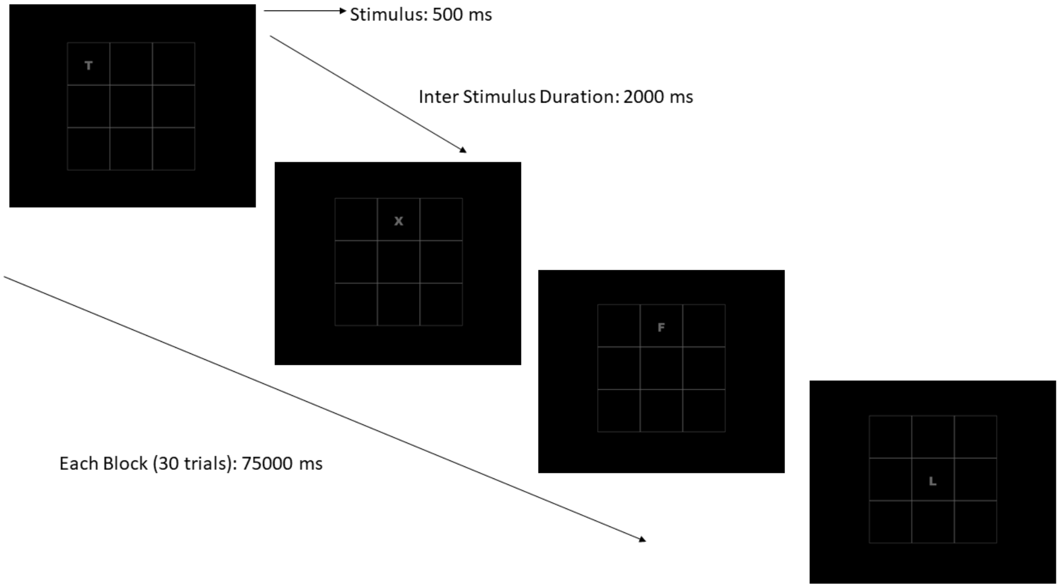


Figure 6: Experiment flow for the dual n-back task used in the study.

A within-subjects repeated measures design was used. There were two conditions: Social Condition for testing the effects of collaboration and Individual Condition as control. In the individual condition, participants performed the experimental task separately. In the social condition, participants did the same task side by side. In order to test for any effect of order of conditions and task switching, task order was counterbalanced within dyads. There was nobody else in the room with the participant/participants in either condition. The researcher left the room after putting on the fNIRS and EEG devices, and starting the data recording. The participant/participants started the experiment by pressing a button on the keyboard.

During the experiment, participant 1 did the letter task in the individual setting, then participant 2 was brought into the lab, and they performed the task together on the same computer (Please see Figure 7), with participant 1 responding to the place and participant 2 responding to the letter. Then, participant 1 left the lab, and participant 2 responded to the letters individually. The order of letter – place task was counterbalanced between dyads, so other dyads followed the mentioned order in reverse, with participant 1 starting with the place task in individual condition. This resulted in sessions as follows: Either Session 1 as participant on the right doing the letter task alone, Session 2 participant on the left doing the letter task and participant on the right doing the place task, Session 3 participant on the left doing the place task alone; or Session 1 as participant on the on the left doing the place task alone, Session 2 participant on the left doing the letter task and participant on the right doing the place task, Session 3 participant on the right doing the letter task alone. Participants never did the same task type on both conditions in order to avoid any effect of learning.

Figure 7: Experiment setup in the study. The computer on the right runs the experiment and the computer on the left is used to collect data from both participants via LSL.

Participants sat in front of the same computer and responded with “z” and “3” buttons on the same keyboard. The computer that ran the task also ran the fNIRS and Enobio measurements for participant on the right side, these recordings were sent to the computer on the left which handled all data recording via the Lab Streaming Layer (LSL) protocol (Kothe, 2014), as well as Enobio and fNIRS measurements of participant on the left side.

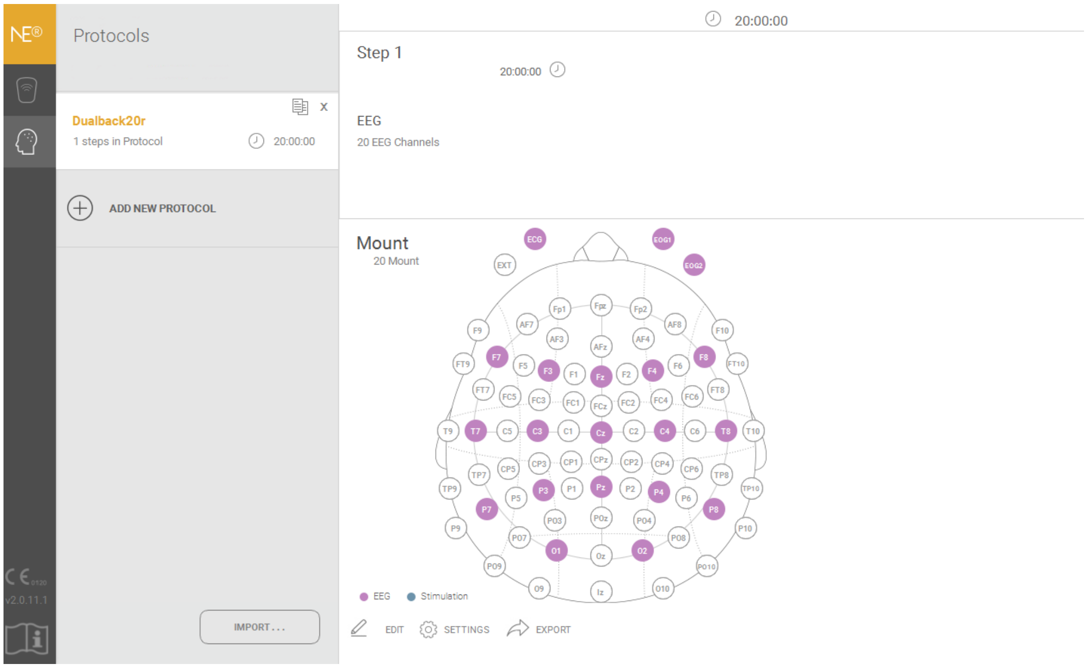
3.3. Data Acquisition

The Edinburgh Inventory of Handedness (Oldfield, 1971) was used to assess participants' handedness (Please see Appendix B.1) and basic demographic data was collected (Please see Appendix B.4). Written consent forms were signed by the participants before the experiment (Please see Appendix B.3). Ten Item Personality Inventory (TIPI) (Gosling et al., 2003) was presented as a questionnaire to participants (Please see Appendix B.2). The evaluation of TIPI provides a score between 1 and 7 points for each of the five personality traits; for example, 1 in extraversion means the person is highly introverted and 7 in extraversion means the person is highly extraverted. Fifty-two participants responded to the questionnaire. Please see Appendix B.2 for the questions in Turkish, as they were presented to the participants.

Data was collected through fNIRS and EEG, individually in control condition and with hyperscanning in the social condition. ECG and EOG recordings were also obtained from both participants in all conditions.

There are types of fNIRS devices such as continuous wave, time-domain and frequency-domain (Pinti et al., 2018). The fNIRS devices used in this study are fNIR Imager 1000 and fNIR Imager 1200 from the company BIOPAC fNIR Devices, which are very similar devices and can be used simultaneously. The system includes a continuous wave NIR spectroscopy control box used for managing the hardware and a computer which is used to operate the COBI Studio software (Ayaz et al., 2012) that handles data acquisition. Both systems were used with two 16-channel sensor pads containing 4 near-infrared light sources and 10 detectors, which were placed over the foreheads of both participants and connected to the control box with 2x6″ cables with 14 pin connectors. Both systems obtain measurements regarding oxygenation from 16 optodes over the prefrontal cortex, which correspond to Brodmann areas 9, 10, 44 and 45. The source-detector separation of the sensor is 2.5 cm, and this allows a penetration depth of 1.25 cm. Such a system is able to assess changes in oxy-hemoglobin (HbO) and deoxy-hemoglobin (HbR) relative concentrations at a temporal resolution of 2 Hz.

Enobio EEG devices (Neuroelectrics, Spain) were used in this study. These devices allow 2-channel EOG and one channel ECG recording. Single channel ECG recordings provide enough data for the assessment of heart rate, heart rate variability, and autonomic balance. Also, EOG and ECG data were used to filter the EEG data from artifacts caused by heartbeat and eye movements. Leaving three channels for these, 17 channels were used for cortical EEG recording. The 20 channels in order were: P7, P4, Cz, Pz, P3, P8, O1, O2, T8, F8, C4, F4, ECG, Fz, C3, F3, EOG1, T7, F7, EOG2 (Please see Figure 8). Sampling rate was 500 Hz.



Protocols

Dualback20r
1 steps in Protocol 20:00:00

Step 1 20:00:00

EEG
20 EEG Channels

Mount
20 Mount

Figure 8: Protocol and placement of electrodes as used in the study.

All measures were logged onto a single .xdf file using Lab Streaming Layer (LSL) (Kothe, 2014). LSL facilitates simultaneous data collection from several machines by transferring data in a local network and saving data with identical timestamps across devices (Gramann et al., 2014). Timestamps are used to achieve synchronization in the data analysis.

3.4. The Analyses

The recorded data was parsed into different files for each participant and modality, with identical timestamps and markers for each participant's responses and task events. Statistical analyses were conducted with IBM SPSS v28.

Behavioral measures consisted of Reaction Times, the Number of Missed Trials, and the Number of Wrong Responses, and d prime (d'). When calculating reaction times, missed trials (when a participant fails to respond in 2000 ms of the stimulus onset) and wrong responses (when the wrong participant responds in the social condition or when a participant responds to a non-target in any condition) were not included in the reaction time analysis. The average reaction time in each n-back level was used to make comparisons. One male participant did not have any correct responses in 3-back level during the social condition.

D prime (d') was calculated as suggested in the literature (Haatveit et al., 2010): For each n-back level, hit rate (correct responses / correct responses + misses) and false alarm rate (false responses in No-Go trials / false responses + correct no responses) were calculated, then Z transformation was done to these rates in a Microsoft Excel spreadsheet using the

NORMSINV formula, and finally d' scores for each n-back level were calculated as the Z transformation of hit rate minus the Z transformation of false alarm rate. Perfect hit rates were adjusted with the formula of 1 – (1/2n), and zero false alarms were adjusted with 1/2n (n being the number of trials in this context). These d' scores were transferred to SPSS and a repeated measures ANOVA was conducted.

ECG analysis was conducted for Heart Rate, Heart Rate Variability, and Autonomic Balance with help from HRVTool (Vollmer, 2019). Data was missing for the social condition of one female participant entirely due to loss of connection with the device. Average heart rates of the participants during each n-back level were calculated as beat per minute values.

EOG data was analyzed regarding blink rate, blink duration, blink rate variability (within-subject deviation of blink rate), and blink duration variability (within-subject deviation of blink duration). These measures were compared across n-back levels, social setting of the task, and extraversion score of participants. In order to normalize the data for any personal differences, the ratio of each n-back level was calculated with regards to 0-back (for example, blink rate in 1-back/blink rate in 0-back) and analyses were conducted on these values.

3.4.1. FNIRS and WTC

For the analysis of fNIRS data, recordings of each n-back level per participant were evaluated manually, and any optode which has raw light intensity values above 4000 mV or below 400 mV were rejected. After filtering with a FIR finite impulse filter to attenuate cardiological and respiratory noise, changes in oxyhemoglobin (HbO) and deoxyhemoglobin (HbR) levels were determined by using the Modified Beer Lambert Law in reference to the rest period of 10 seconds at the beginning of each n-back level as the baseline. Afterward, the mean HbO and HbR change for each optode was calculated. For each optode and n-back level, any data point that is further than 2 z-scores were removed before proceeding with the analysis. Then, mean HbO change for each n-back level was analyzed with a repeated measures ANOVA separately for each optode, with n-back levels (0-, 1-, 2-, 3-back) and task condition (Individual or Social) as variables and gender, first condition and task type as covariates. This was repeated for the HbR measure as well.

In order to measure the relation among fNIRS signals from co-actors, Wavelet transform coherence (WTC) was used (X. Cui et al., 2012). WTC is used to assess neural synchronization between participants, as phase lag between the time series obtained from corresponding fNIRS channels of both participants and the amplitude of their coherence is analyzed as a function of frequency and time. For evaluating the results of wavelet transform coherence analysis of fNIRS data, NBS-Predict Toolbox was used (Serin et al., 2021).

WTC analysis was conducted on fNIRS data, for both HbO and HbR. For this, first Modified Beer-Lambert Law was applied to fNIRS data from all participants to calculate

HbO and HbR values with a MATLAB (Mathworks, Natick, MA, USA) pipeline. Afterwards, Wavelet Transform Coherence was calculated on HbO and HbR values separately with a MATLAB code modified from a previous work (Küskü, 2022). WTC was conducted per n-back block and since each block lasted 75 seconds, and the frequency of the fNIRS devices were 2 Hz, a period of 256 was chosen which corresponds to a frequency of 0.0078125 Hz (Yargıçoğlu, 2022). Due to data disruption or failure to understand the task in one member of the dyad, a total of six dyads had to be left out. WTC was conducted on 25 remaining dyads comparing each optode with every optode from the other dyad member for each n-back level during social task setting. For comparing the interbrain and intrabrain coherence results of different n-back levels, the NBS-Predict Toolbox (Serin et al., 2021) was used with a 2x2 classification analysis, and the BrainNet viewer add-on (Xia et al., 2013) of the same toolbox was used to draw weighted networks on brain surface.

3.4.2. EEG and ERP

For power spectrum analysis on EEG data, EEGLAB Toolbox was used (Delorme & Makeig, 2004). The data was imported and then basic FIR filter was applied with 0.5 Hz - 40 Hz band pass filter. Afterwards data cleaning was conducted with Clean Rawdata and Artifact Subspace Reconstruction of EEGLAB toolbox (Onton et al., 2005), and after that all data were re-referenced to average.

For EEG-Hyperscanning, HyPyp was used to assess interbrain and intrabrain connectivity (Ayrolles et al., 2021) which includes functions from MNE-Python (Gramfort et al., 2013). Before the analysis, all data was epoched over trials (Go trial for Left Participant, Go trial for Right Participant, No-Go trial) with EEGLAB. Seven dyads had to be discarded because of disrupted data and two dyads were discarded because one member failed to understand the task, leaving 22 dyads in the analysis. In both power spectrum analysis and hyperscanning, data was analyzed in five frequency bands: Delta (0.5 - 3.5 Hz), Theta (4 - 7.5 Hz), Alpha (8 - 12 Hz), Beta (12.5 - 29.5 Hz), Gamma (30 - 40 Hz).

Event Related Potential (ERP) Analysis was conducted using MATLAB with the following toolboxes: EEGLAB Toolbox (Delorme & Makeig, 2004), ERPLAB Toolbox (Lopez-Calderon & Luck, 2014), Mass Univariate ERP Toolbox (Groppe et al., 2011).

First, ERP sets were created with 7 bins:

1) Correct response to letter target stimulus

2) Correct response to place target stimulus

3) Correct response to non-target stimulus (in other words, no response)

4) Missed trial (participant did not give any response to a target stimulus)

5) Wrong response to non-target stimulus (participant responded when s/he should not)

6) Wrong response to letter target stimulus (please see below)

7) Wrong response to place target stimulus

Bins number 6 and 7 were rare and almost exclusively occurred during the social condition when one of the participants responded to a stimulus even though the other participant in the dyad was supposed to respond.

With the implementation of these bins, ERP sets were analyzed for any effect regarding these bins as well as the four n-back levels (0 to 3), two social conditions (alone, social), and the extraversion score of the participants in TIPI (introvert, extravert). The other aspects of TIPI were not included in these analyses since earlier work pointed towards the extraversion score to be most associated with the outcome, and it was preferred to focus on that in the previous TMC. Still, it is possible to analyze the created ERP sets based on other measures in TIPI (Agreeableness, Conscientiousness, Emotional Stability, Openness) if the same sets are grouped accordingly.

Using Mass Univariate Toolbox, each ERP comparison (for example, 0-back vs. 1-back, or Individual 2-back vs. Social 2-back, or Extraverts 3-back Social vs. Introverts 3-back Social, and so on) was submitted to a repeated measures, two-tailed permutation test based on the tmax statistic (Blair & Karniski, 1993). A family-wise alpha level of 0.05 was used. The test included all 17 cortical electrodes with a time range of 100 to 800 ms. For each comparison, repeated measures t-tests were performed with 2500 random within-participant permutations and the original data, resulting in 2501 sets of tests. Among these tests, the most extreme t-score (dubbed “tmax”) was used for estimating the tmax distribution of the null hypothesis that there was no significant difference between these conditions. In all tests, Bonferroni test-wise alpha was 0.000008. This estimation was followed with derivation of critical t-scores. Please refer to the ERP subsection of Results section for details.

CHAPTER 4

RESULTS

The collected data was analyzed for behavioral, EEG, fNIRS, EOG and ECG measures across n-back levels for individual and social task settings, and extraversion score of participants in TIPI. Before the analysis, data from two male participants were left out because after the experiment they revealed that they did not understand the task, and their behavioral data supported their claim as both had zero correct responses in several n-back levels.

4.1. Behavioral Measures

Behavioral measures consisted of Reaction Times, Number of Missed Trials, Number of Wrong Responses, and d prime (d').

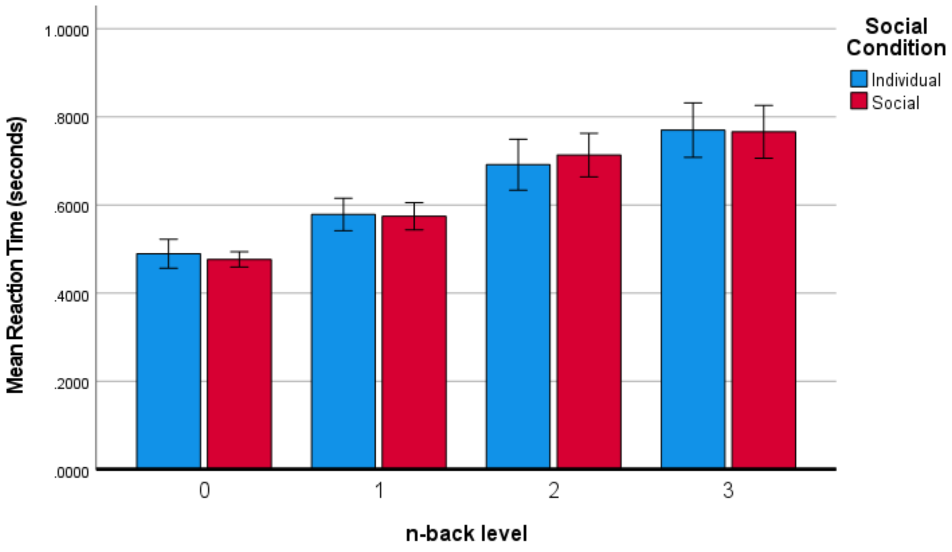
When calculating reaction times, missed trials (when participant fails to respond in 2000 ms of the stimulus onset) and wrong responses (when the wrong participant responds in the social condition or when a participant responds to a non-target in any condition) were not included in the reaction time analysis. Average reaction time in each n-back level was used to make comparisons. One male participant did not have any correct responses in 3-back level during social condition, and therefore could not be included in reaction times analysis.

Reaction times were analyzed with a repeated measures ANOVA on n-back levels (0, 1, 2, 3-back) across task condition (Individual, Social), with covariates of gender, task type (Letter, Place), and which condition the participant started with (Individual First, Social First). Simple Contrast was applied to n-back levels with 0-back as the reference. Sidak correction was used on multiple comparisons. Mauchly's test of sphericity was significant ($W(5) = .614$, $p < .001$) so Greenhouse-Geiser correction was applied.

The results revealed that none of the covariates had any significant effect. Males and females had similar reaction times ($F(1, 55) = .179$, $p > .05$, $\eta_p^2 = .003$), so did participants who started in the individual condition or social condition ($F(1, 55) = .852$, $p > .05$, $\eta_p^2 =$

.015). Reaction times during Letter and Place tasks were similar as well (*F*(1, 55) = .508, $p > .05$, $\eta_p^2 = .009$).

Average reaction time difference between individual and social condition was not significant for any n-back level (all levels combined: *F*(1, 55) = .916, $p > .05$, $\eta_p^2 = .016$), whereas the difference between n-back levels were significant (*F*(2.064, 113.516) = 28.524, $p < .001$, $\eta_p^2 = .342$) (Please see Figure 9). The interaction of n-back level and task condition was not significant (F(2.383, 131.071) = .66, $p > .05$, $\eta_p^2 = .012$).



Covariates appearing in the model are evaluated at the following values: Gender = .53, FirstCondition = .51, TaskType = .51

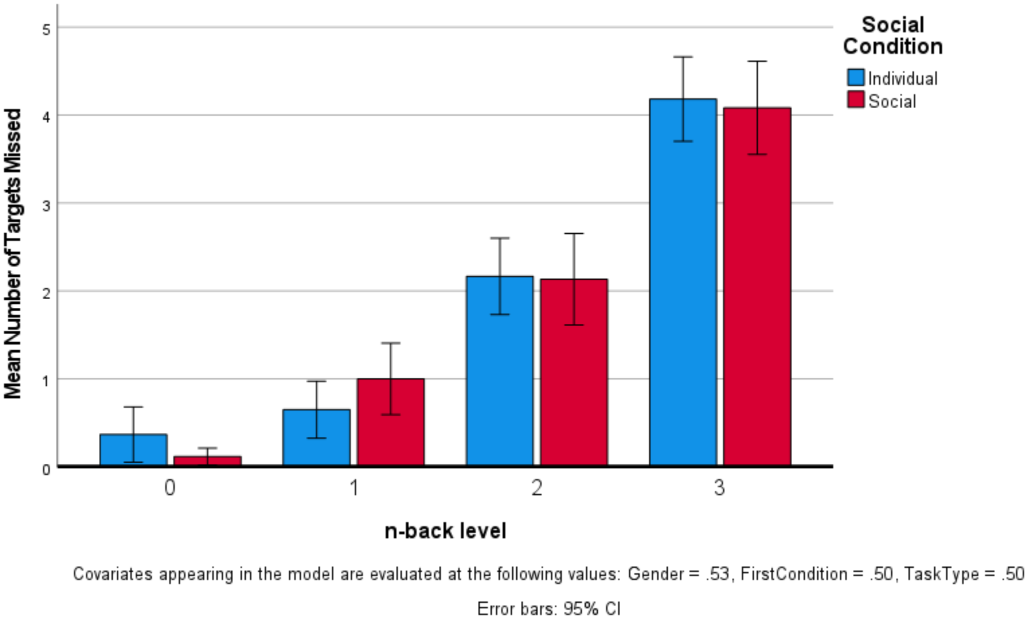
Error bars: 95% CI

Figure 9: Average reaction times across n-back levels for each task condition. Error bars show 95% Confidence Interval.

A repeated measures ANOVA was conducted to analyze the Number of Missed Trials, with n-back levels (0-, 1-, 2-, 3-back) across task condition (Individual, Social). Gender, task type (Letter, Place), and which condition the participant started with (Individual First, Social First) were entered as covariates. Simple Contrast with 0-back as the reference was preferred. For multiple comparisons, Sidak correction was applied. Mauchly's test of sphericity was significant (W(5) = .788, $p < .05$) so Greenhouse-Geiser correction was applied.

The difference between individual and social condition on missed trials was not significant for any n-back level (all levels combined: F(1, 56) = .073, $p > .05$, $\eta_p^2 = .001$), whereas the difference between n-back levels were significant (F(2.773, 155.301) = 43.463, $p < .001$, $\eta_p^2 = .437$) (Please see Figure 10). The interaction of n-back level and task condition was not significant (F(2.651, 148.446) = .981, $p > .05$, $\eta_p^2 = .005$.

None of the covariates had any significant effect on the results. Males and females had similar number of missed trials (F(1, 56) = .955, $p > .05$, $\eta_p^2 = .017$), so did participants who started with individual condition or social condition (F(1, 56) = .066, $p > .05$, $\eta_p^2 = .001$). Number of missed trials during Letter task and Place task were similar as well (F(1, 56) = .066, $p > .05$, $\eta_p^2 = .001$).



Covariates appearing in the model are evaluated at the following values: Gender = .53, FirstCondition = .50, TaskType = .50

Error bars: 95% CI

Figure 10: The number of missed trials for individual and social conditions across n-back levels. Error bars show 95% Confidence Interval.

The number of wrong responses were analyzed with a repeated measures ANOVA on n-back levels (0-, 1-, 2-, 3-back) across task condition (Individual, Social). Covariates were dyad's gender, type of task (Letter, Place), and first condition of the participant (Individual First, Social First). Simple Contrast was used on the n-back levels with 0-back as the reference. Sidak correction was applied for the multiple comparisons. Mauchly's test of sphericity was significant (W(5) = .519, $p < .001$) so Greenhouse-Geiser correction was applied.

The results revealed that none of the covariates had any significant effect. Males and females had similar wrong responses (F(1, 56) = .291, $p > .05$, $\eta_p^2 = .005$), so did participants who started with individual condition or social condition (F(1, 56) = 1.268, $p > .05$, $\eta_p^2 = .022$). Wrong responses during Letter task and Place task were similar as well (F(1, 56) = 1.032, $p > .05$, $\eta_p^2 = .018$).

Task condition did not cause a difference in the number of wrong responses for any n-back level (all levels combined: F(1, 56) = .038, $p > .05$, $\eta_p^2 = .001$). On the other hand, n-back level had a significant effect (F(2.218, 124.205) = 8.945, $p < .001$, $\eta_p^2 = .138$) (Please see Figure 11). The interaction of n-back level and task condition was not significant (F(2.063, 251.576) = 2.977, $p > .05$, $\eta_p^2 = .05$). Follow-up paired-samples t-tests revealed a significant difference between individual 0-back and social 0-back (t(59) = 2.912, $p < .01$, $d = .37$)

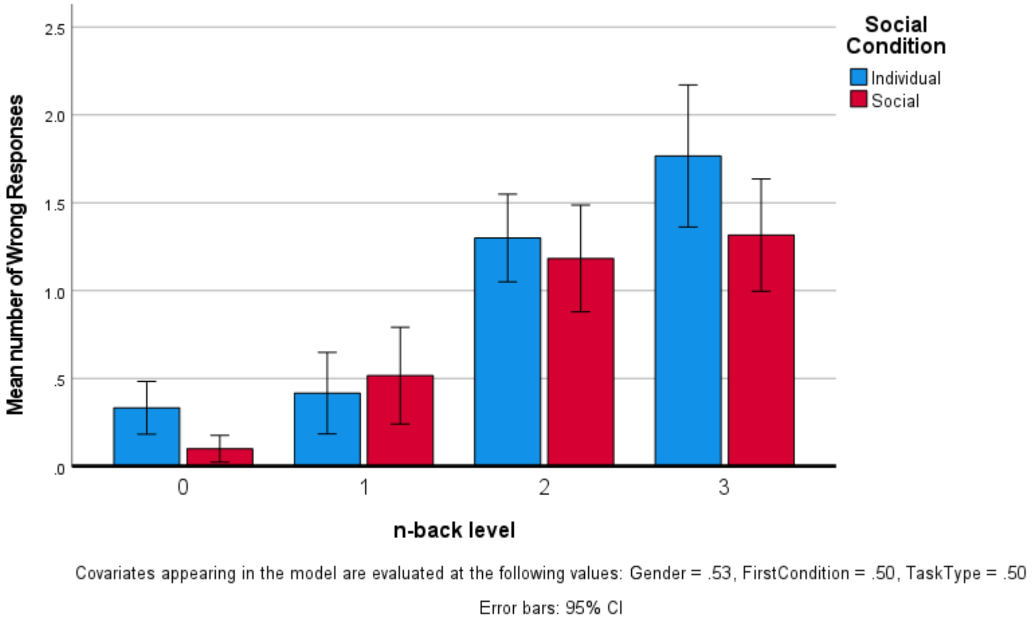


Figure 11: The number of wrong responses for individual and social conditions across n-back levels. Error bars show 95% Confidence Interval.

D prime (d') scores were analyzed with a repeated measures ANOVA on n-back levels (0-, 1-, 2-, 3-back) across task condition (Individual, Social), with covariates of gender, task type (Letter, Place), and which condition the participant started with (Individual First, Social First). Simple Contrast was applied to n-back levels with 0-back as the reference. Sidak correction was used on multiple comparisons. Mauchly's test of sphericity was not significant (W(5) = .85, $p = .119$).

The results revealed that none of the covariates had any significant effect. Males and females had similar d' scores (F(1, 56) = .225, $p > .05$, $\eta_p^2 = .004$), so did participants who started with individual condition or social condition (F(1, 56) = .103, $p > .05$, $\eta_p^2 = .002$). D prime scores during Letter task and Place task were similar as well (F(1, 56) = .158, $p > .05$, $\eta_p^2 = .003$).

Task condition did not cause a difference in the d' scores: F(1, 56) = .106, $p > .05$, $\eta_p^2 = .002$). On the other hand, n-back level had a significant effect (F(3, 168) = 48.235, $p < .001$, $\eta_p^2 = .463$) (Please see Figure 12). The interaction of n-back level and task condition was not significant (F(3, 168) = 1.457, $p > .05$, $\eta_p^2 = .025$). Follow-up paired-samples t-tests revealed a significant difference between individual 0-back and social 0-back (t(59) = -2.228, $p < .05$, $d = -.29$)

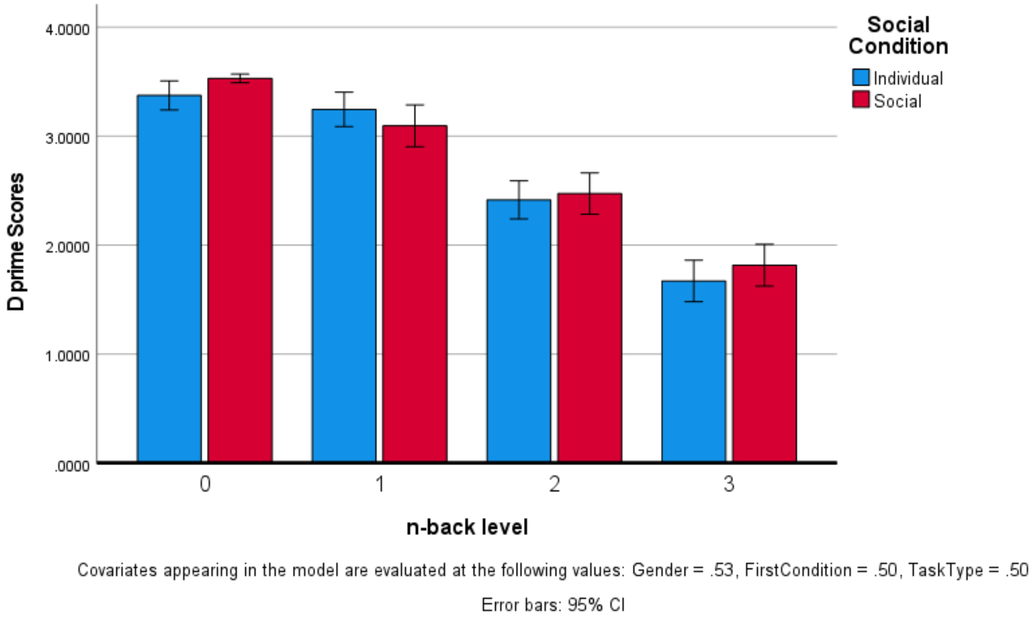


Figure 12: The d prime scores for individual and social conditions across n-back levels. Error bars show 95% Confidence Interval.

Behavioral measures did not yield any significant effect due to the social task setting. There was no relation between extraversion and reaction times, number of wrong responses, number of missed trials, and d prime scores.

4.2. Personality Scores

In this section, results of the analyses regarding personality traits will be summarized. First, results of the Ten Item Personality Inventory (TIPI) scores will be presented.

Descriptive statistics of TIPI scores showed that participants had the following average values on each trait, with standard error in parentheses: 4.89 (.14) in extraversion, 4.88 (.11) in agreeableness, 5.16 (.13) in conscientiousness, 4.37 (.11) in emotional stability, and 5.75 (.1) in openness. Relation between TIPI scores and other measures were analyzed with correlation analysis, One-Way ANOVA tests and Repeated Measures ANOVA tests.

For correlation analyses, TIPI score of each trait was taken as an interval variable. Each TIPI trait was correlated against that participant's measure in that modality (e.g. reaction time) in every n-back level for both conditions, resulting in 8 correlations per trait (0-back individual, 0-back social, 1-back individual, 1-back social, 2-back individual, 2-back social, 3-back individual, 3-back social). Difference between task conditions for each n-back level was calculated and correlation and One-Way ANOVA analyses were conducted over these values as well.

For ANOVA tests, participants were divided into two groups for their TIPI scores in each trait. Participants who scored 4 and below were put into one group and who scored above 4 were out into another group. For example, introvert group and extravert group for Extraversion trait. Then, repeated measures ANOVA tests were conducted for each trait, with trait group as independent variable and participant's measure of the same n-back level in two task conditions as the repeated measure (e.g. Introvert Group and Extravert Group on 0-back individual reaction time and 0-back social condition reaction time was one test). This was repeated for other n-back levels. One-Way ANOVA tests were conducted to assess whether there was an effect of trait group on each of the eight experiment blocks (0-back individual, 0-back social, 1-back individual, 1-back social, 2-back individual, 2-back social, 3-back individual, 3-back social) separately. Please see Table 1 for the number of participants in each personality trait group.

Table 1: Distribution of participants among personality trait groups.

Trait	**Score ≤ 4**	**Score > 4**
Extraversion	16	36
Agreeableness	15	37
Conscientiousness	14	38
Emotional Stability	20	32
Openness	4	48

In the fourth Thesis Monitoring Committee, it was suggested that focusing on the extraversion aspect of TIPI would be better than handling all 5 measures. Therefore, in the rest of this document only extraversion will be presented. In short, the only other aspect that has shown a significant effect with social condition was agreeableness which had a similar but smaller relation to social task setting as extraversion. Conscientiousness showed small effects in higher n-back levels regardless of social condition, Emotional Stability showed a minor correlation with ECG measures, and Openness was not studied due to very few data points in the low openness score group.

4.3. ECG Measures

ECG analysis was conducted for Heart Rate, Heart Rate Variability, and Autonomic Balance. Data was missing for the social condition of one female participant entirely due to loss of connection with the device, and in some other sessions data was obtained for some n-back levels but connection was lost afterwards, or the data was too noisy for a proper measure of heart rate, leaving a total of 49 participants in the ECG analyses.

Average heart rates of the participants during each n-back level were calculated as beat per minute values. This data was analyzed with a repeated measures ANOVA on n-back levels (0-, 1-, 2-, 3-back) across task condition (Individual, Social), with covariates of gender, task type (Letter, Place), and which condition the participant started with (Individual First, Social First). Simple Contrast was applied to the n-back levels with 0-back as the reference. Sidak correction was applied for the multiple comparisons. Mauchly's test of sphericity was significant (W(5) = .569, $p < .001$) so Greenhouse-Geiser correction was applied.

None of the covariates had a significant effect. Males and females had similar heart rates (F(1, 45) = .296, $p > .05$, $\eta_p^2 = .002$), so did participants who started with individual condition or social condition (F(1, 45) = .791, $p > .05$, $\eta_p^2 = .003$). Reaction times during Letter task and Place task were similar as well (F(1, 45) = .27, $p > .05$, $\eta_p^2 < .001$).

Average heart rate difference between individual and social condition was significant (all levels combined: F(1, 45) = 6.235, $p < .05$, $\eta_p^2 = .122$). There was a significant effect of the n-back level (F(2.293, 103.173) = 3.692, $p < .05$, $\eta_p^2 = .076$). The interaction of n-back level and task condition was not significant (F(2.149, 96.701) = .748, $p > .05$, $\eta_p^2 = .016$).

Heart Rate Variability analysis was conducted on SDNN (standard deviation of N-N intervals) measure, which is regarded as the gold standard (Shaffer & Ginsberg, 2017) among other measures of heart rate variability such as Root-Mean-Square of Successive Differences (RMSSD) and percentage of N-N intervals that differ more than 50 ms (pNN50). For this analysis, the interval between each normal heart beat is measured (N-N interval) and then the standard deviation is calculated for these intervals. Then a repeated measures ANOVA was conducted on n-back levels (0-, 1-, 2-, 3-back) across task condition (Individual, Social). The first condition of the participant (Individual First, Social First), gender of the dyad, and type of the task (Letter, Place) were covariates. Simple Contrast was applied to the n-back levels with 0-back as the reference point. Sidak correction was applied for the multiple comparisons. Mauchly's test of sphericity was significant (W(5) = .52, $p < .001$) so Greenhouse-Geiser correction was applied.

There was no significant difference in the results regarding any of the covariates. Both genders had similar heart rate variability (F(1, 45) = .769, $p > .05$, $\eta_p^2 = .018$). Starting with the individual condition or the social condition did not have an effect on heart rate variability (F(1, 45) = .009, $p > .05$, $\eta_p^2 = 0$). Type of the task, whether it was Letter or Place, did not change heart rate variability (F(1, 45) = .076, $p > .05$, $\eta_p^2 = .02$).

Task condition did not have a significant effect for any n-back level (all levels combined: F(1, 45) = .003, $p > .05$, $\eta_p^2 < .001$). There was a significant effect of the n-back level (F(2.274, 102.333) = 3.209, $p < .05$, $\eta_p^2 = .067$). The interaction of n-back level and task condition was not significant (F(2.353, 105.875) = .158, $p > .05$, $\eta_p^2 = .004$).

Table 2: Descriptive statistics for Heart Rate (bpm) and Heart Rate Variability (SDNN).

Individual	**Heart Rate (M, SE)**	**HRV (M, SE)**	**Social**	**Heart Rate (M, SE)**	**HRV (M, SE)**
0-back	81.6 (1.66)	54.3 (4.11)	**0-back**	80.52 (1.7)	58.43 (5.57)
1-back	83.11(1.59)	52.57 (4.27)	**1-back**	82.14 (1.57)	51.57 (4.47)
2-back	84.49 (1.65)	47.83 (3.42)	**2-back**	83.03 (1.61)	44.61 (2.47)
3-back	84.52 (1.66)	50.4 (3.51)	**3-back**	83.69 (1.54)	44.53 (2.89)

ECG results did not yield any significant effect of extraversion on heart rate and heart rate variability.

Finally, Autonomic Balance analysis was conducted on ECG data, which shows the relation between parasympathetic nervous system, which is active during rest, digestion and sleep, and sympathetic nervous system, which is associated with fight or flight response and has increased activation during more exciting, stressful situations (Valenza et al., 2018). In the literature, Autonomic Balance is assessed as the ratio of Low Frequency to High Frequency waves in ECG (Dogru et al., 2009) or the ratio of Perpendicular Standard Deviation to Linear Standard Deviation in Poincare Plot of ECG waves (Yılmaz et al., 2018), as in both, the former is an indicator for parasympathetic nervous system activation and the latter is an indicator for the sympathetic nervous system activation. In this study, analysis of Autonomic Balance did not yield any significant results, most likely due to the duration of data collection since Autonomic Balance provides better information when data is collected over prolonged periods of time, from 1-hour to a 24-Hour-long Holter ECG (Kobayashi et al., 2014).

4.4. EOG Measures

EOG data was analyzed regarding blink rate, blink duration, blink rate variability (within-subject deviation of blink rate), and blink duration variability (within-subject deviation of blink duration). These measures were compared across n-back levels, social setting of the task, and extraversion score of participants.

In order to normalize the data for any personal differences, the ratio of each n-back level was calculated with regards to 0-back (e.g. blink rate in 1-back/blink rate in 0-back) and analyses were conducted on these values.

The differences between n-back levels in either social setting were analyzed with Repeated Measures ANOVAs with Simple (First) contrast and the results were not significant for blink rate, blink duration, and their respective within-subject deviations.

Paired samples t-tests were used to compare the blink rates during social condition to the individual setting. The only difference was found in the 3-back condition (i.e. ratio of blink rate in 3-back/blink rate in 0-back). In particular, participants had significantly higher blink rate ratio in social condition (M = 1.16, SE = .09) than individual action (M = .94, SE = .04) during the 3-back condition (t(54) = -2.134, $p < .05$, d = -.29). 1-back and 2-back ratios were not significant (Please see Figure 13).

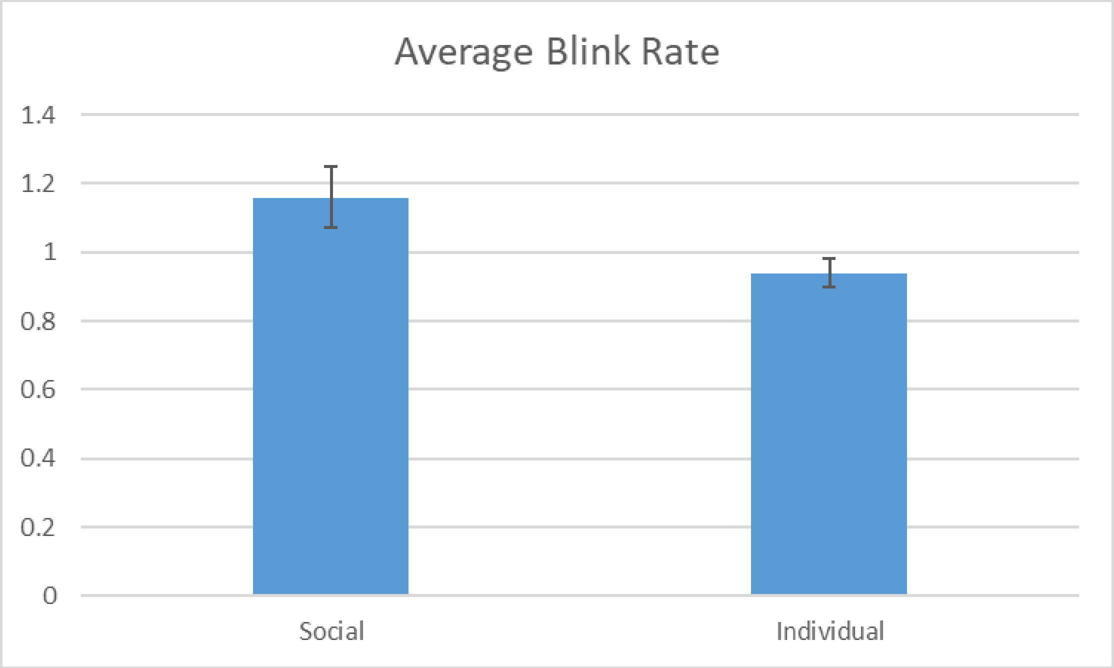


Figure 13: Average Blink Rate for social condition and individual action during 3-back.

There was no significant effect for blink rate variability, blink duration and blink duration variability.

One-way ANOVA with Simple (the first level as the reference) contrast was used to compare the introverts and the extraverts in each n-back level in each social setting (individual, social), and no significant effect was found for blink rates, blink durations, and blink duration variability.

There was a significant, albeit small, effect on blink rate variability during social condition at the 2-back level (i.e. ratio of 2-back to 0-back) as indicated by one-way ANOVA test results F(1, 44) = 4.109, $p < .05$, $\eta_p^2 = .087$. In particular, blink rate variability was lower in extraverts (M = .91, SE = .06) compared to introverts (M = 1.17, SE = .13) (Please see Figure 14). Other comparisons did not yield any significant effects.

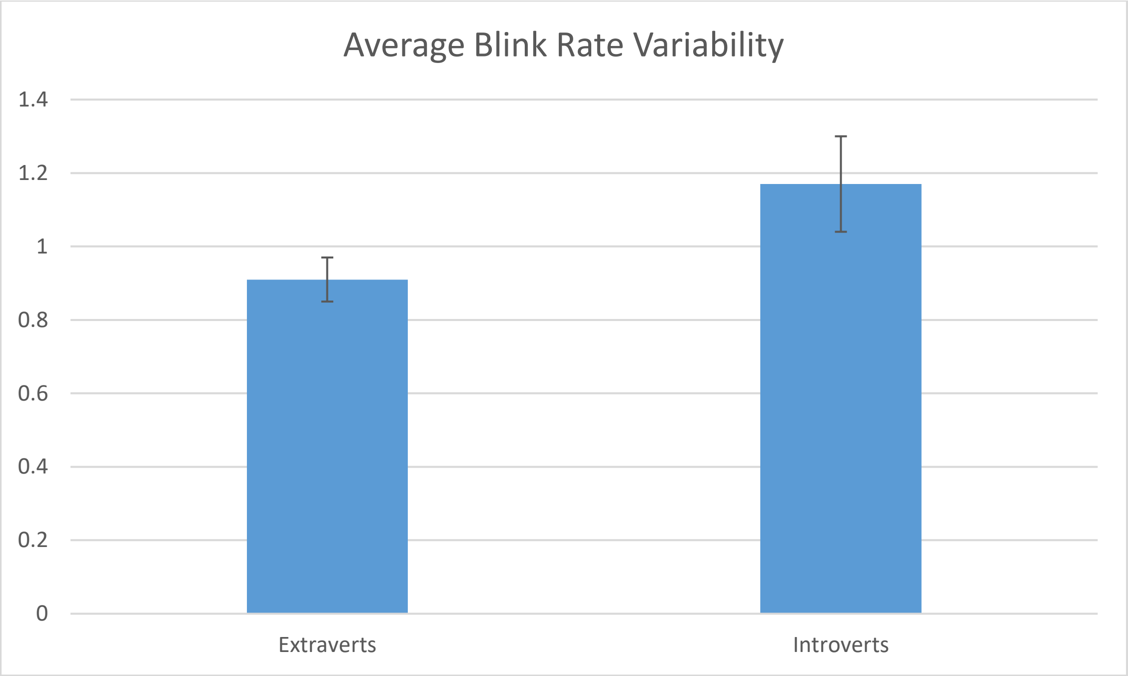


Figure 14: Blink Rate Variability for extravert and introvert participants during social 2-back. Error bars show standard error.

4.5. Individual fNIRS Analysis

For the analysis of fNIRS data, recordings of each n-back level per participant were evaluated manually and any optode which has values above 4000 mV or below 400 mV were rejected since such recordings fall outside the recording range of the photodetectors of the utilized fNIRS system. After filtering with the finite impulse response (FIR) filter, changes in oxyhemoglobin (HbO) and deoxyhemoglobin (HbR) levels were determined with respect to the rest period of 10 seconds in the beginning of each n-back level as the baseline. Afterwards, mean HbO and HbR change for each optode was calculated. For each optode and n-back level, any data point that is further than 2 z-scores were removed before proceeding with the analysis over average HbO and HbR values.

Average HbO change for each n-back level was analyzed with a repeated measures ANOVA separately for each optode, with n-back levels (0-, 1-, 2-, 3-back) and task condition (Individual or Social) as variables and gender, first condition and task type as covariates, and paired samples t-tests as follow-up tests. Another repeated measures ANOVA with the same variables, covariates, and follow-up tests was repeated for the HbR measure as well. Finally, False Discovery Rate (FDR) correction (Benjamini & Hochberg, 1995) was applied over all comparisons. Please refer to Table 3 (HbO) and Table 4 (HbR) for all comparisons that had a significant result (FDR corrected $p < 0.05$) after FDR correction.

Table 3: Results of Oxygenation Change Analyses over n-back levels in HbO.

Optode	**Descriptives**	**Statistics**
5	3-back (*M* = .33, *SE* = .05) and 1-back (*M* = .15, *SE* = .05) and 2-back (*M* = .12, *SE* = .06)	3-back vs. 1-back *t*(75) = 2.022, *d* = .23 and 2-back *t*(76) = 2.117, *d* = .24
11	3-back (*M* = .31, *SE* = .06) and 2-back (*M* = .15, *SE* = .05)	*t*(82) = 2.211, *d* = .24
15	2-back (*M* = .22, *SE* = .07) and 0-back (*M* = .38, *SE* = .08)	*t*(79) = -2.015, *d* = -.22

Table 4: Results of Oxygenation Change Analyses over n-back levels in HbR.

Optode	**Descriptives**	**Statistics**
2	3-back (*M* = .03, *SE* = .04) and 0-back (*M* = -.09, *SE* = .05), and 1-back (*M* = -.11, *SE* = .03), and 2-back (*M* = -.11, *SE* = .04)	3 vs. 0-back *t*(77) = 2.319, *d* = .26 ; vs. 1-back *t*(83) = 2.524, *d* = .27 ; vs. 2-back *t*(84) = 2.492, *d* = .26
4	3-back (*M* = .08, *SE* = .03) and 0-back (*M* = -.12, *SE* = .04), and 1-back (*M* = -.09, *SE* = .02), and 2-back (*M* = -.06, *SE* = .03)	3 vs. 0-back *t*(81) = 3.82, *d* = .42 ; vs. 1-back *t*(80) = 3.832, *d* = .43 ; vs. 2-back *t*(80) = 3.138, *d* = .35
6	3-back (*M* = .11, *SE* = .04) and 1-back (*M* = -.01, *SE* = .03) and 2-back (*M* = -.02, *SE* = .03)	3-back vs. 1-back *t*(61) = 3.68, *d* = .47; vs. 2-back *t*(65) = 2.138, *d* = .26
8	3-back (*M* = .13, *SE* = .04) and 0-back (*M* = .01, *SE* = .04), and 2-back (*M* = -.01, *SE* = .03)	3-back vs. 0-back *t*(68) = 2.11, *d* = .25 and 2-back *t*(69) = 2.552, *d* = .29
9	3-back (*M* = .15, *SE* = .04) and 1-back (*M* = .04, *SE* = .05)	*t*(67) = 2.048, *d* = .25
10	3-back (*M* = .14, *SE* = .04) and 2-back (*M* = .11, *SE* = .03), vs. 1-back (*M* = -.04, *SE* = -.03)	1-back vs. 2-back *t*(60) = -3.045, *d* = .37; and vs. 3-back *t*(63) = -3.312, *d* = .39
11	3-back (*M* = .15, *SE* = .05) and 1-back (*M* = -.03, *SE* = .04)	*t*(82) = 3.443, *d* = .38
12	3-back (*M* = .16, *SE* = .04) and 0-back (*M* = .02, *SE* = .04), and 1-back (*M* = -.02, *SE* = .03), and 2-back (*M* = .02, *SE* = .03)	3-back vs. 0-back *t*(70) = 2.565, *d* = .30 ; vs. 1-back *t*(69) = 3.394, *d* = .41 ; vs. 2-back *t*(72) = 3.318, *d* = .39
14	3-back (*M* = .03, *SE* = .03) and 0-back (*M* = -.06, *SE* = .03)	*t*(77) = 2.216, *d* = .25
15	3-back (*M* = .04, *SE* = .05) and 0-back (*M* = -.14, *SE* = .05)	*t*(76) = 2.619, *d* = .30

Please refer to Table 5 for all significant (FDR corrected $p < 0.05$) comparisons regarding the social setting of the task in HbO measure.

Table 5: Results of Oxygenation Change Analysis over social setting of the task in HbO.

Optode	**Descriptives**	**Statistics**
3	0-back social (*M* = .16, *SE* = .08), individual (*M* = .32, *SE* = .07)	*t*(42) = 1.917, *d* = .29
8	2-back social (*M* = .06, *SE* = .06), individual (*M* = .29, *SE* = .09)	*t*(33) = 2.446, *d* = .42
10	0-back social (*M* = .24, *SE* = .08), individual (*M* = .06, *SE* = .1)	*t*(28) = -1.961, *d* = .30
14	2-back social (*M* = .31, *SE* = .09), individual (*M* = .23, *SE* = .07)	*t*(37) = 2.115, *d* = .34

Please see Table 6 for all significant (FDR corrected $p < 0.05$) comparisons regarding the social setting of the task in HbR measure.

Table 6: Results of Oxygenation Change Analysis over social setting of the task in HbR.

Optode	**Descriptives**	**Statistics**
2	1-back social (*M* = -.03, *SE* = .06), individual (*M* = -.17, *SE* = .06)	*t*(39) = -2.059, *d* = -.32
3	1-back social (*M* = -.01, *SE* = .06), individual (*M* = -.17, *SE* = .07)	*t*(44) = -1.951, *d* = -.29
10	0-back social (*M* = -.08, *SE* = .06), individual (*M* = .15, *SE* = .07)	*t*(27) = 2.881, *d* = .54
11	1-back social (*M* = -.14, *SE* = .06), individual (*M* = .09, *SE* = .06)	*t*(39) = 2.548, *d* = .40
12	0-back social (*M* = -.1, *SE* = .05), individual (*M* = .06, *SE* = .07)	*t*(30) = 2.413, *d* = .43
13	0-back social (*M* = -.17, *SE* = .06), individual (*M* = .08, *SE* = .09)	*t*(40) = 2.718, *d* = .42
14	0-back social (*M* = -.12, *SE* = .05), individual (*M* = -.01, *SE* = .05)	*t*(36) = 1.988, *d* = .33
14	1-back social (*M* = .04, *SE* = .05), individual (*M* = -.04, *SE* = .04)	*t*(37) = -1.874, *d* = -.30
16	0-back social (*M* = -.12, *SE* = .06), individual (*M* = .05, *SE* = .04)	*t*(37) = 3.053, *d* = .49
16	2-back social (*M* = .02, *SE* = .05), individual (*M* = -.1, *SE* = .06)	*t*(39) = -2.283, *d* = -.36

The results of fNIRS analysis were represented in topography plots. For this, values of degree of freedom of the conducted analysis and degree of freedom of the error of the conducted analysis were extracted from ANOVAs done in SPSS and critical F-values were calculated to use as threshold values. Then, F-values from ANOVAs were extracted as a text file and imported into fNIRSoft and loaded into a topography plot. The critical F-values that were calculated before were entered as dual thresholds. Please see the following figures for topography plots. In the rest of this thesis work, all topography plots were drawn with this method.

Please see Figure 15 for the effect of n-back level on HbO (left) and HbR (right) levels.

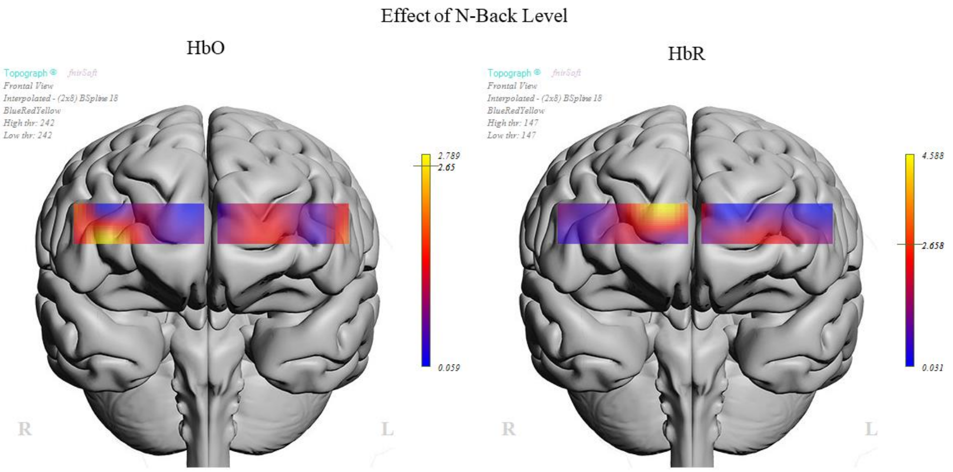


Figure 15: The effect of n-back level on HbO (left) and HbR (right) levels.

Please see Figure 16 for the effect of social setting on HbO (left) and HbR (right) levels.

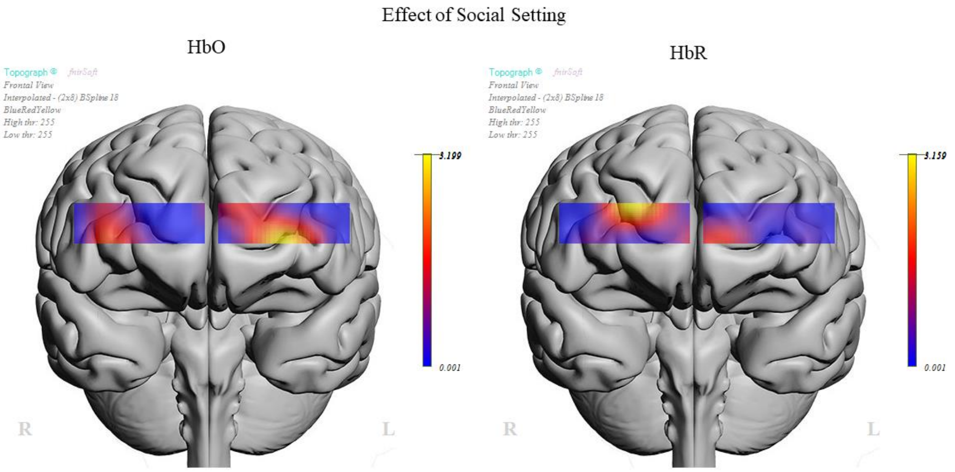


Figure 16: The effect of social setting on HbO (left) and HbR (right) levels.

Please see Figure 17 for the effect of interaction between n-back level and social setting on HbO (left) and HbR (right) levels.

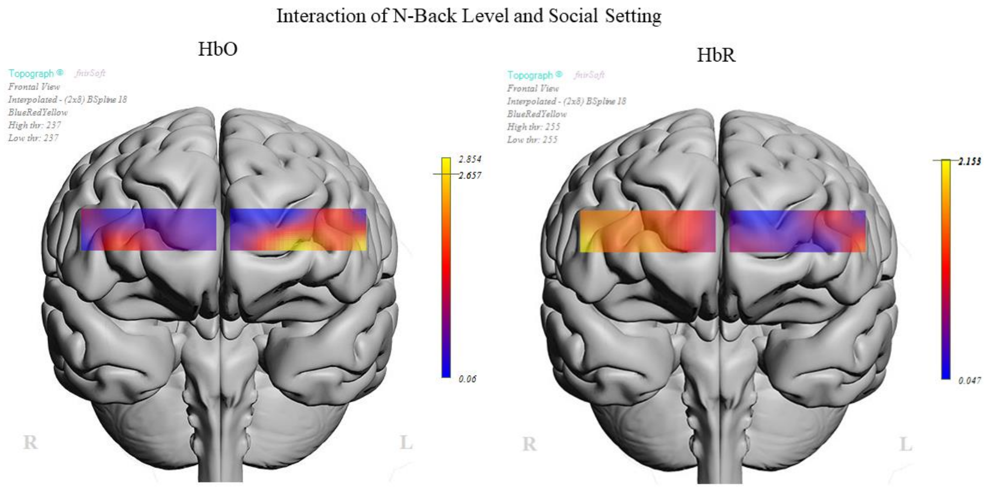


Figure 17: The effect of interaction between n-back level and social setting on HbO (left) and HbR (right) levels.

In order to assess the effect of the extraversion score of the participant on the fNIRS measure, the average HbO and HbR values from the analyses explained above separated into two groups: Introverts (Extraversion score ≤ 4) and Extraverts (Extraversion score > 4). These two groups were entered as a between subjects variable to the repeated measures ANOVA design explained above and the analyses were repeated for HbO and HbR measures. After FDR correction, only HbO measure had significant results. Please see Table 7 for the comparisons that had a significant result after FDR correction.

Table 7: Significant results in fNIRS regarding extraversion in HbO.

Optode	Mean (Standard Error)	Statistics
8	Introverts: -.08 (.08) Extraverts: .22 (.04)	$F(1, 20) = 10.269$, $p < .05$, $\eta_p^2 = .339$
9	Introverts: .1 (.06) Extraverts: .29 (.04)	$F(1, 19) = 6.396$, $p < .05$, $\eta_p^2 = .252$
13	Introverts: -.02 (.07) Extraverts: .29 (.05)	$F(1, 21) = 12.296$, $p < .05$, $\eta_p^2 = .369$
15	Introverts: .07 (.08) Extraverts: .32 (.06)	$F(1, 25) = 5.881$, $p < .05$, $\eta_p^2 = .19$

In order to keep this report brief, it was avoided to report every participant’s recording in detail. As an example: Participant 25L, a 21-years-old male who started with social condition, had a very strong effect of task condition: Heart rate was very high in social condition (between 118 – 131 bpm across levels, which is higher than the average in the experiment population as well as regular heart rate range for humans) compared to the individual condition (83 – 93 bpm, similar to experiment population and general heart rate in healthy population). The recorded data was double-checked to ensure this difference could not be amounted to an error in recording and everything seemed to be in order. Also, his responses were slower in social condition albeit faster than experiment population average in both conditions, which are also in line with him being overly-excited in the social condition. His fNIRS data also corroborated these effects. TIPI results were extraversion 6, agreeableness 3.5, conscientiousness 6.5, emotional stability 5.5, openness 7. Please see Figure 18 for fNIRS data.

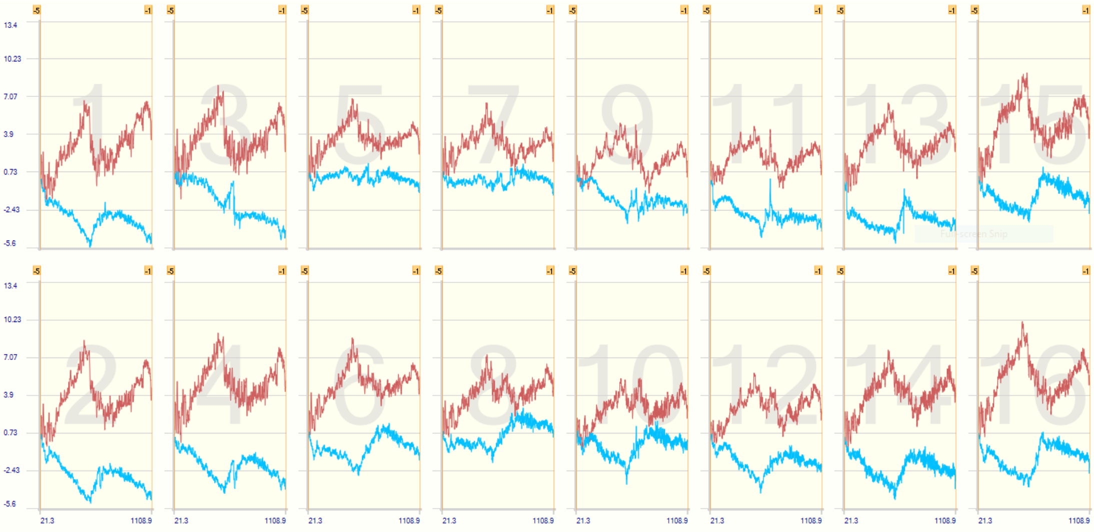


Figure 18: Participant 25L fNIRS data for 16 optodes separately. First half of data belongs to social condition and latter to individual condition. Pink line is HbO and blue line is HbR.

4.6.Wavelet Transform Coherence

Wavelet Transform Coherence (WTC) analysis was conducted on fNIRS data, for both HbO and HbR. For this, first Modified Beer-Lambert Law was applied to fNIRS data from all participants to calculate HbO and HbR values. Afterwards, Wavelet Transform Coherence was conducted on HbO and HbR values separately with a MATLAB code modified from a previous work (Küskü, 2022). Due to data disruption or failure to understand the task in one member of the dyad, 6 dyads had to be left out and both the interbrain and intrabrain analyses were conducted on 25 remaining dyads.

4.6.1. Interbrain Coherence

Interbrain WTC in fNIRS analysis was performed by comparing each optode with every optode from the other dyad member for each n-back level during social task setting. Please see Figure 19 for an example.

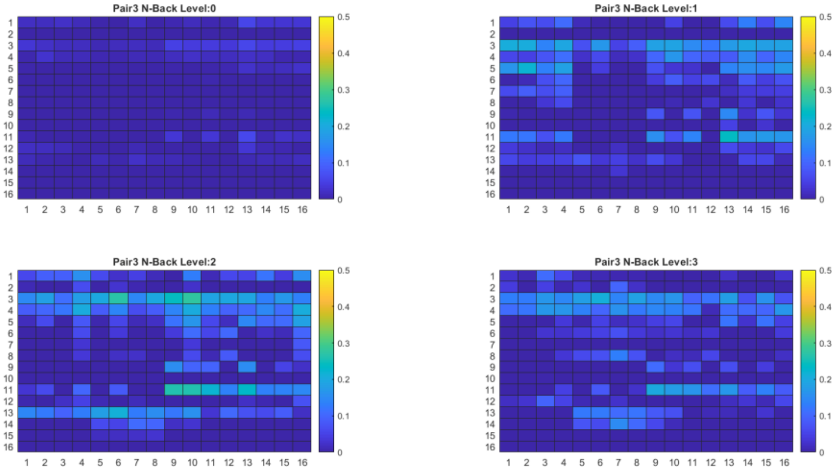


Figure 19: WTC results of Dyad 3 during social task setting HbO data.

The same analysis was applied to data from the same participants during the individual task setting as a control group. Please see Figure 20 for the output from the same pair from the example above.

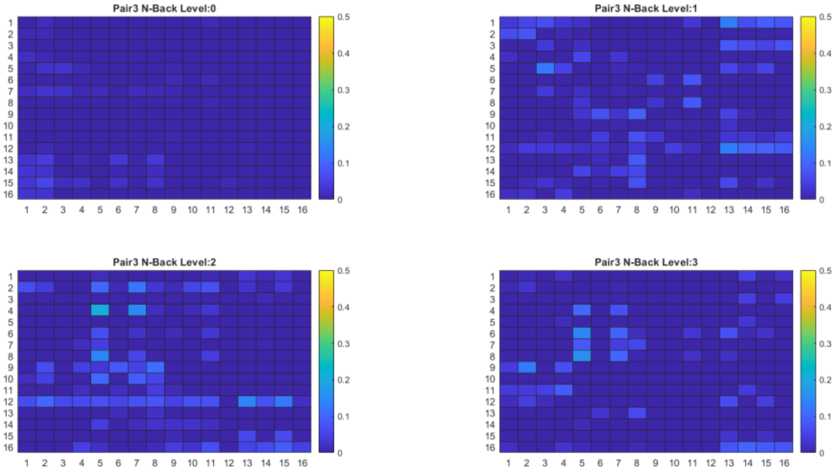


Figure 20: WTC results of Dyad 3 during individual task setting HbO data.

From the results of WTC analyses, data comparing the same optodes from dyads (for example optode 1 x optode 1, optode 2 x optode 2, …) were extracted to SPSS. Repeated Measures ANOVA was conducted with n-back levels (0-, 1-, 2-, 3-back) across task condition (Individual, Social). Only the n-back level showed significant effects after FDR correction. Please see Table 8 for all comparisons and results, with p values after FDR correction.

Table 8: All comparisons in fNIRS WTC between same optodes of participants.

Optode	**HbO Statistics**	**HbR Statistics**
1	$F(3, 72) = 5.368$, $p < .05$, $\eta_p^2 = .183$	$F(3, 72) = 12.936$, $p < .05$, $\eta_p^2 = .35$
2	$F(3, 72) = 6.934$, $p < .05$, $\eta_p^2 = .224$	$F(3, 72) = 8.964$, $p < .05$, $\eta_p^2 = .272$
3	$F(3, 72) = 3.201$, $p < .05$, $\eta_p^2 = .118$	$F(3, 72) = 8.439$, $p < .05$, $\eta_p^2 = .26$
4	$F(3, 72) = 2.44$, $p > .05$, $\eta_p^2 = .092$	$F(3, 72) = 9.622$, $p < .05$, $\eta_p^2 = .286$
5	$F(3, 72) = 1.007$, $p > .05$, $\eta_p^2 = .04$	$F(3, 72) = 7.256$, $p < .05$, $\eta_p^2 = .232$
6	$F(3, 72) = 2.938$, $p < .05$, $\eta_p^2 = .109$	$F(3, 72) = 4.348$, $p < .05$, $\eta_p^2 = .153$
7	$F(3, 72) = 4.107$, $p < .05$, $\eta_p^2 = .146$	$F(3, 72) = 3.141$, $p < .05$, $\eta_p^2 = .116$
8	$F(3, 72) = 3.307$, $p < .05$, $\eta_p^2 = .121$	$F(3, 72) = 8.906$, $p < .05$, $\eta_p^2 = .271$
9	$F(3, 72) = 5.288$, $p < .05$, $\eta_p^2 = .181$	$F(3, 72) = 3.544$, $p < .05$, $\eta_p^2 = .129$
10	$F(3, 72) = 4.204$, $p < .05$, $\eta_p^2 = .149$	$F(3, 72) = 5.398$, $p < .05$, $\eta_p^2 = .184$
11	$F(3, 72) = 6.551$, $p < .05$, $\eta_p^2 = .214$	$F(3, 72) = 1.586$, $p > .05$, $\eta_p^2 = .062$
12	$F(3, 72) = 5.099$, $p < .05$, $\eta_p^2 = .175$	$F(3, 72) = 5.826$, $p < .05$, $\eta_p^2 = .195$
13	$F(3, 72) = 6.716$, $p < .05$, $\eta_p^2 = .219$	$F(3, 72) = 9.299$, $p < .05$, $\eta_p^2 = .279$
14	$F(3, 72) = 3.807$, $p < .05$, $\eta_p^2 = .137$	$F(3, 72) = 14.105$, $p < .05$, $\eta_p^2 = .37$
15	$F(3, 72) = 6.51$, $p < .05$, $\eta_p^2 = .213$	$F(3, 72) = 6.609$, $p < .05$, $\eta_p^2 = .216$
16	$F(3, 72) = 6.615$, $p < .05$, $\eta_p^2 = .216$	$F(3, 72) = 2.959$, $p < .05$, $\eta_p^2 = .11$

F-values for each optode were calculated and transferred to fNIRSoft for producing topography plots. Please see Figure 21 for topography plot showing the interaction of task condition and n-back level. This figure and all figures onward show both HbO data on left and HbR data on right.

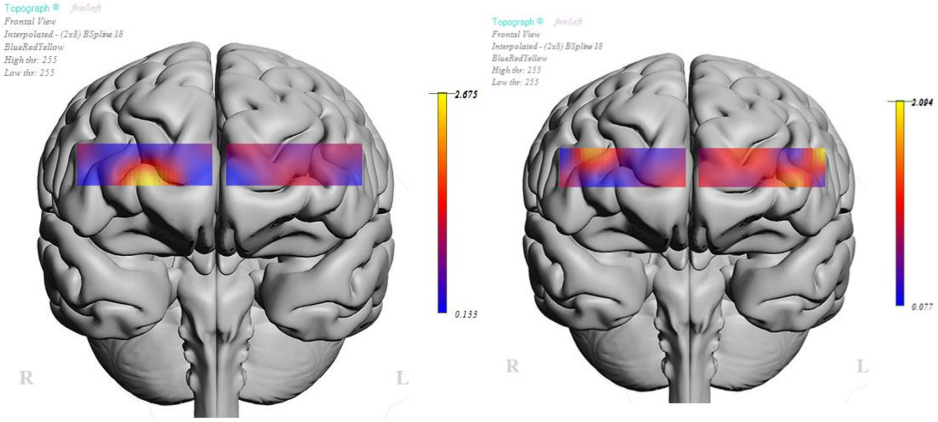


Figure 21: Topography plot for the interaction of n-back level and task setting. HbO on left and HbR on right.

Please see Figure 22 for topography plot showing the effect of task condition.

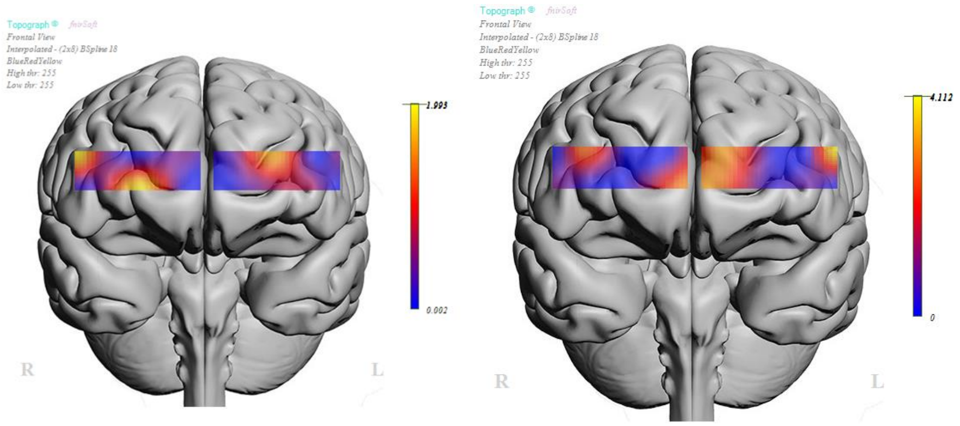


Figure 22: Topography plot for task setting. HbO on left and HbR on right.

Please see Figure 23 for topography plot showing the effect of n-back level.

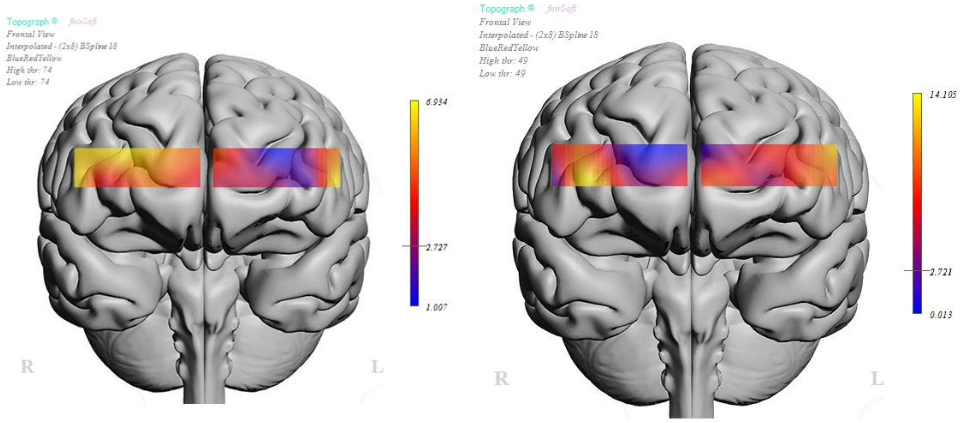


Figure 23: Topography plot for n-back level. HbO on left and HbR on right.

NBS-Predict toolbox (Serin et al., 2021) was used for comparing all optodes with all other optodes (for example optode 1 of participant on the left side x optode 2 of the participant on the right side). This was conducted as a 2x2 classification analysis with two n-back levels of control data made from mock dyads and two n-back levels of real cooperative data. Weighted networks on brain surface were drawns using BrainNet viewer add-on (Xia et al., 2013).

For HbO and HbR, there were significant results only on the comparisons of 0-back to other n-back levels. The result of comparing 0-back and 1-back is seen in Figure 24 and 25 for HbO, and Figure 26 and 27 for HbR.

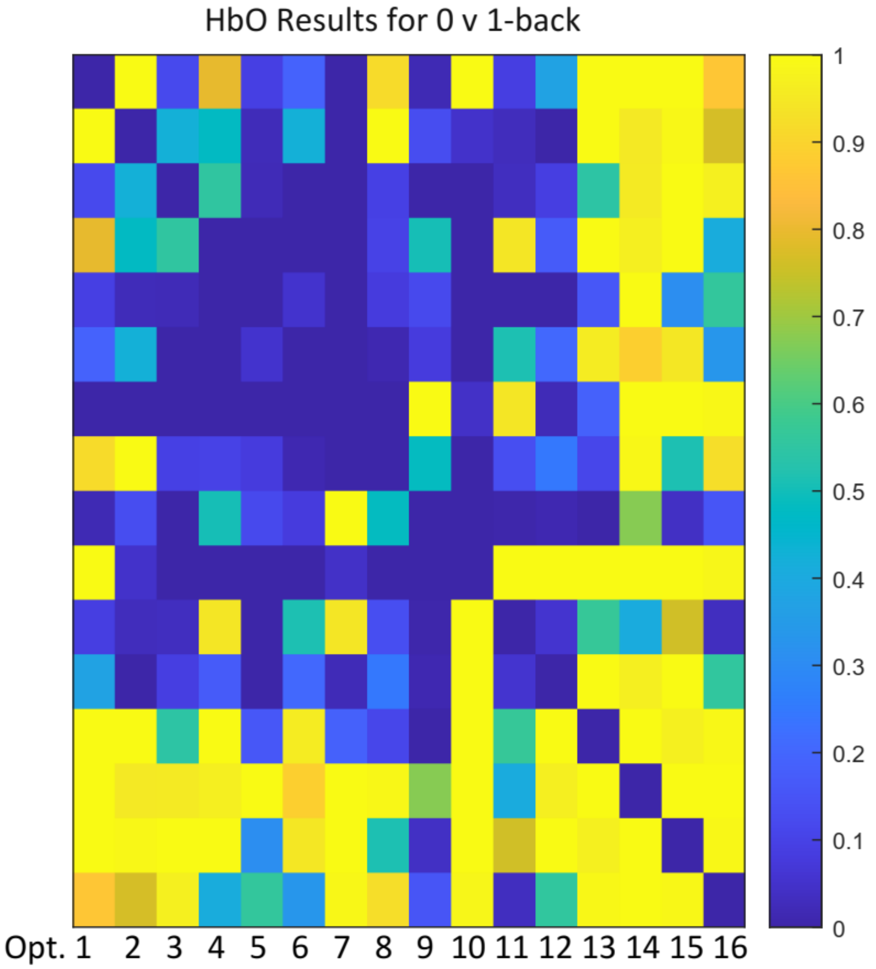


Figure 24: Significant results for the comparison of 0-back and 1-back levels in HbO.

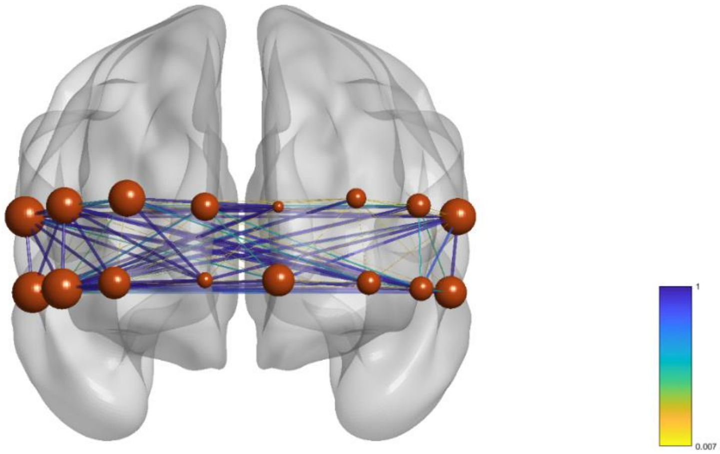


Figure 25: Topography of significant results for the comparison of 0-back and 1-back levels in HbO.

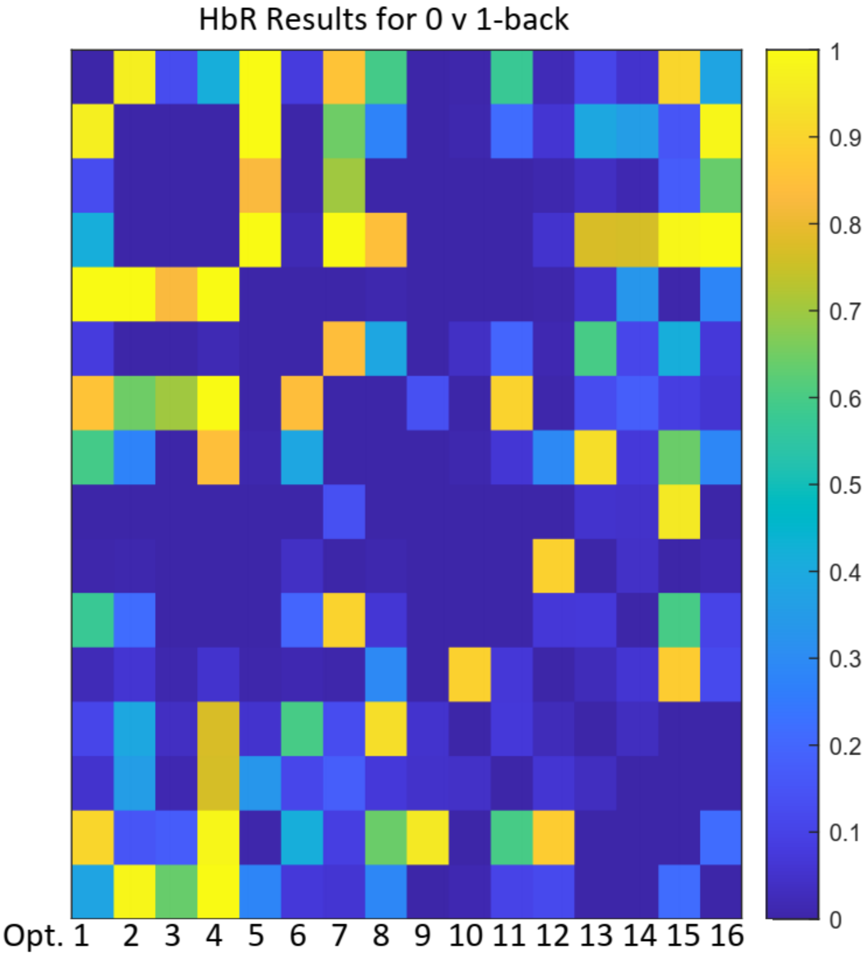


Figure 26: Significant results for the comparison of 0-back and 1-back levels in HbR.

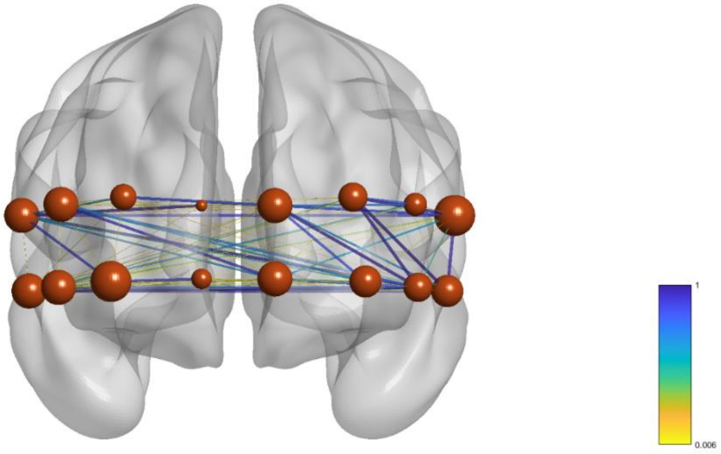


Figure 27: Topography of significant results for the comparison of 0-back and 1-back levels in HbR.

The result of 0- vs. 2-back is seen in Figures 28 and 29 for HbO, and 30 and 31 for HbR.

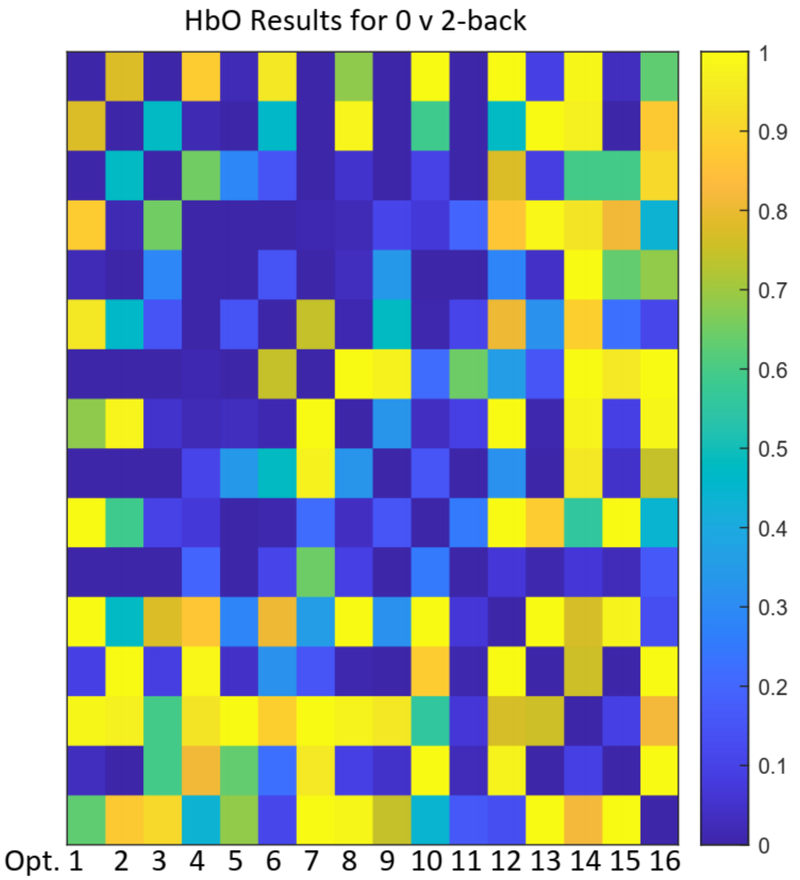


Figure 28: Significant results for the comparison of 0-back and 2-back levels in HbO.

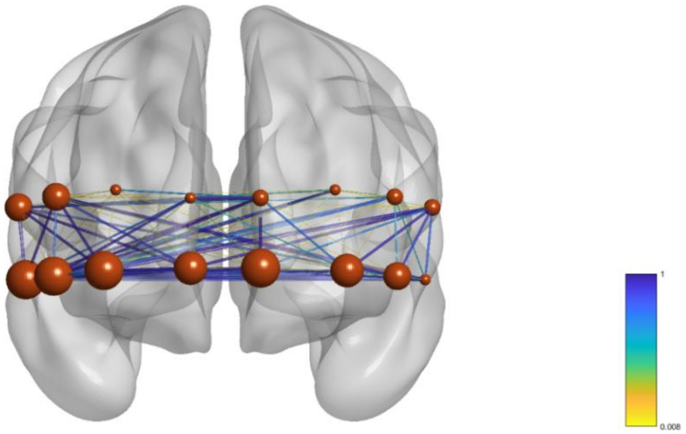


Figure 29: Topography of significant results for the comparison of 0-back and 2-back levels in HbO.

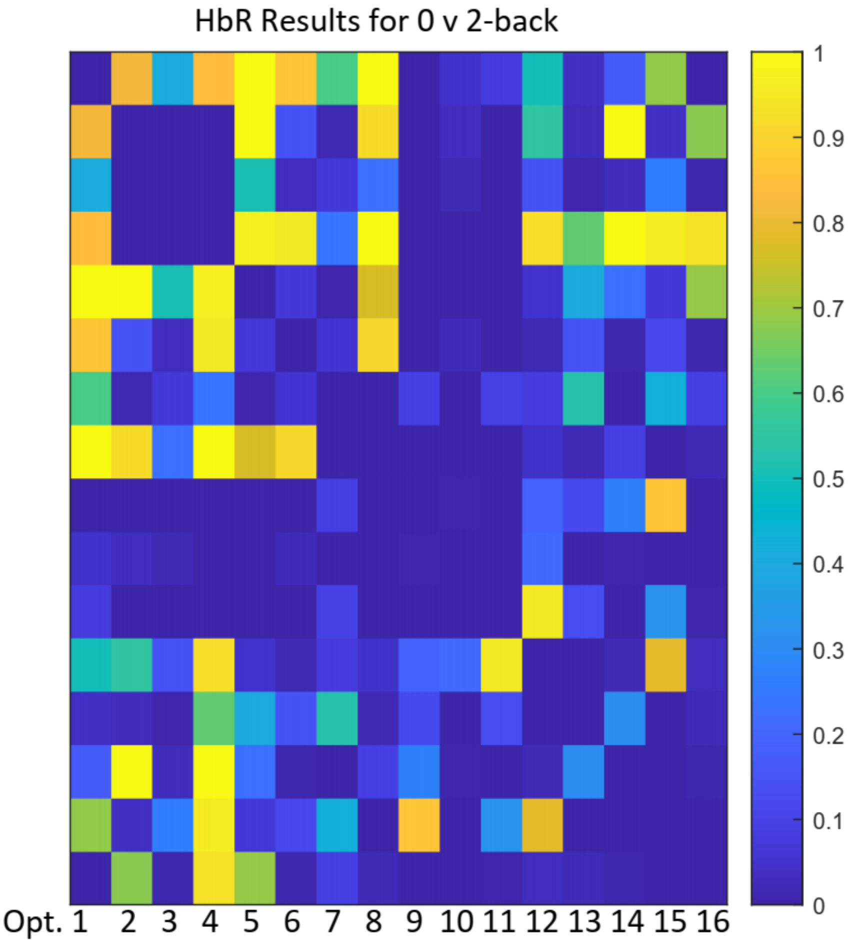


Figure 30: Significant results for the comparison of 0-back and 2-back levels in HbR.

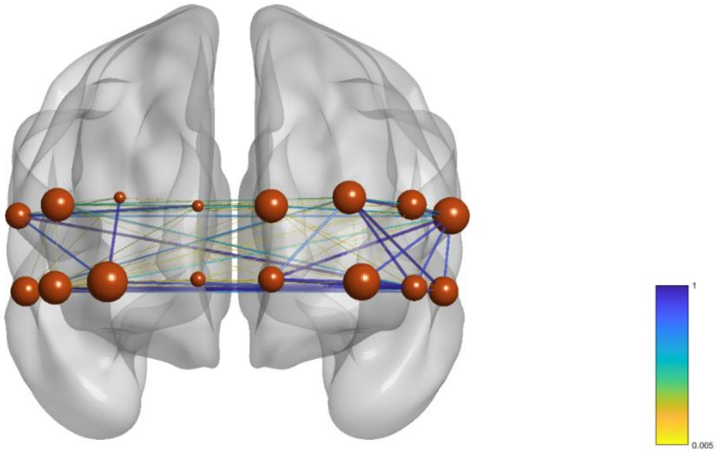


Figure 31: Topography of significant results for the comparison of 0-back and 2-back levels in HbR.

The result of 0- vs. 3-back is seen in Figures 32 and 33 for HbO, and 34 and 35 for HbR.

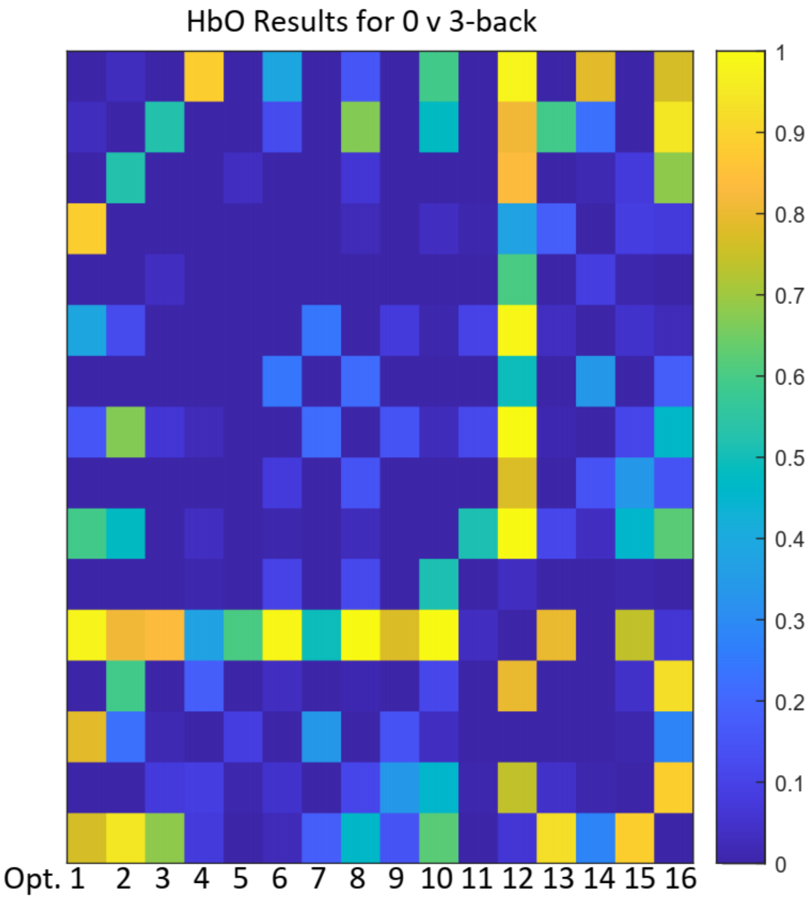


Figure 32: Significant results for the comparison of 0-back and 3-back levels in HbO.

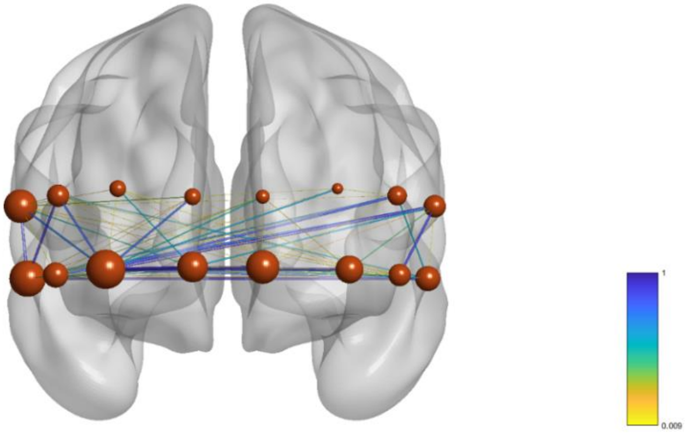


Figure 33: Topography of significant results for the comparison of 0-back and 3-back levels in HbO.

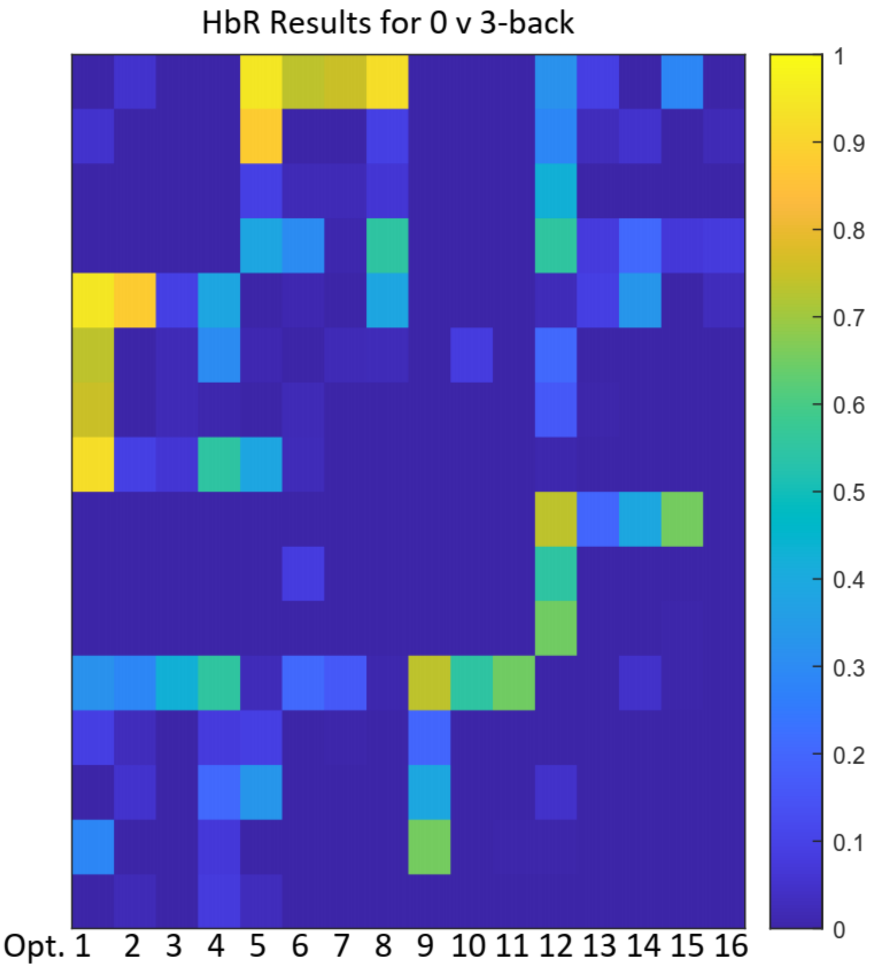


Figure 34: Significant results for the comparison of 0-back and 3-back levels in HbR.

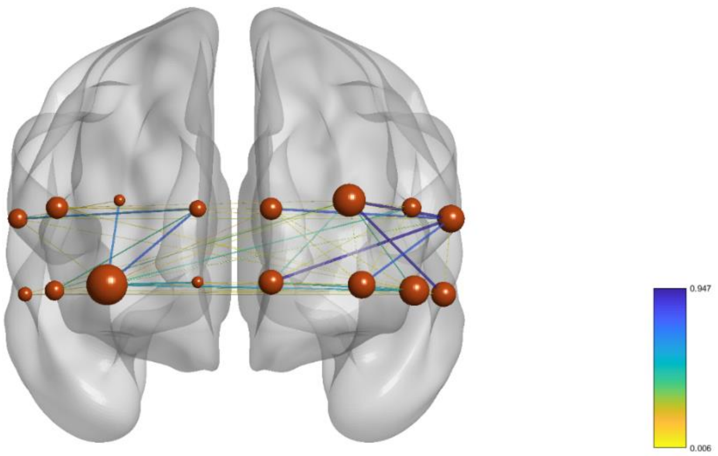


Figure 35: Topography of significant results for the comparison of 0-back and 3-back levels in HbR.

4.6.2. Intrabrain Coherence

Intrabrain WTC in fNIRS analysis was conducted to assess intrabrain coherence, with entering the fNIR data from the same participant as if it was a dyad. Control group was the data from the same participant in the individual task setting. For HbO, the only significant result was seen on the comparison of 0-back to 1-back level, which can be seen in Figure 36 and 37.

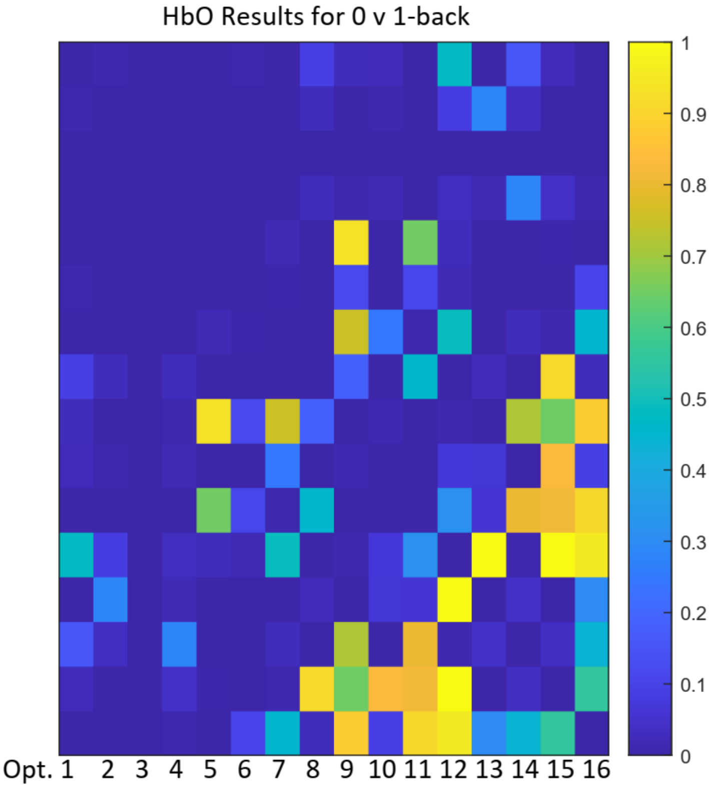


Figure 36: Significant results for the intrabrain comparison of 0-back and 1-back levels in HbO.

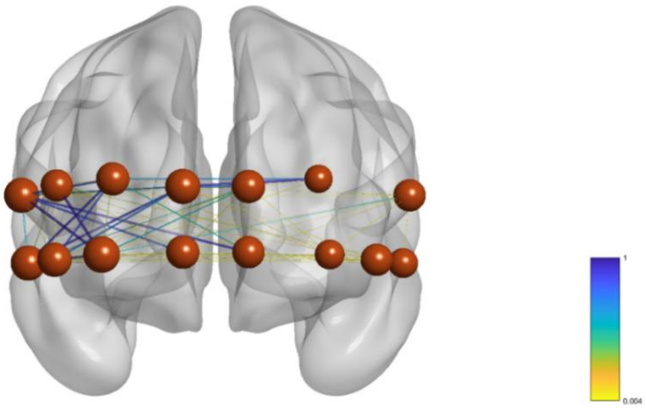


Figure 37: Topography of Significant results for the intrabrain comparison of 0- and 1-back in HbO.

Intrabrain coherence in HbR showed significant results across all comparisons. The result of comparing 0-back and 1-back is seen in Figure 38 and 39.

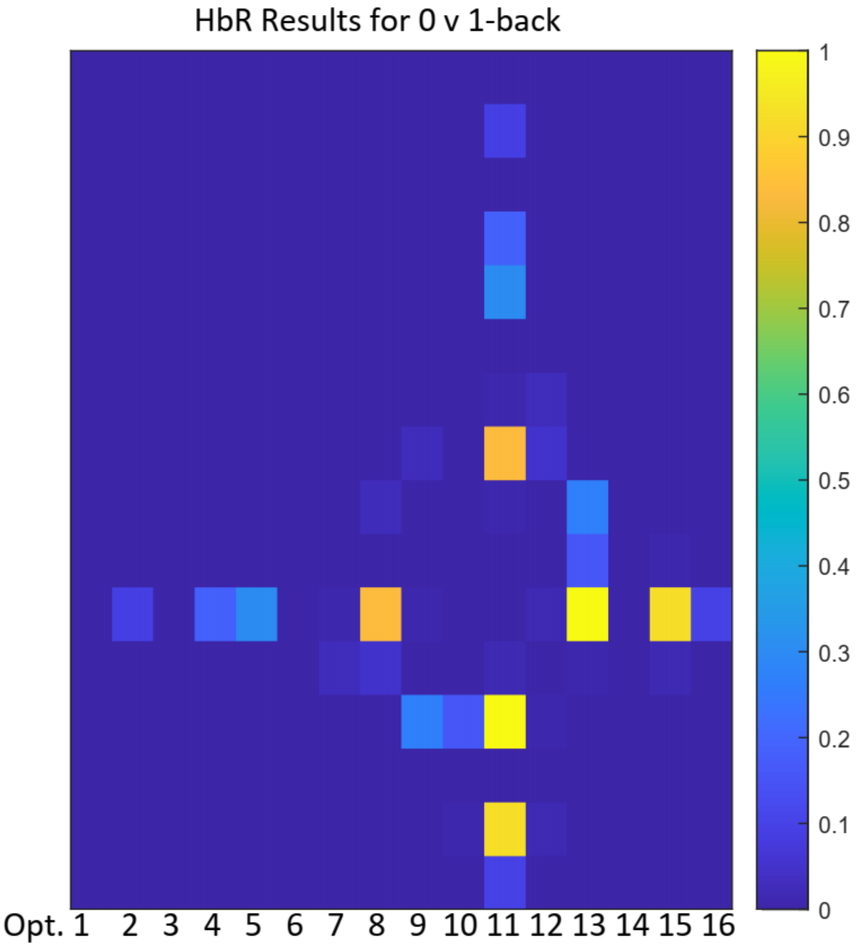


Figure 38: Significant results for the intrabrain comparison of 0-back and 1-back levels in HbR.

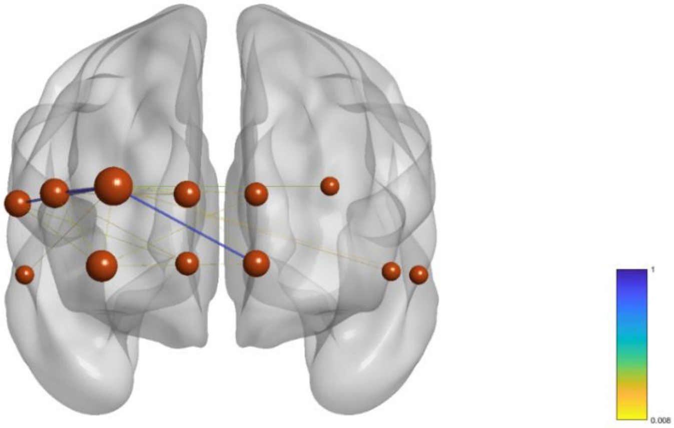


Figure 39: Topography of significant results for the intrabrain comparison of 0- and 1-back in HbR.

The result of comparing the 0-back level and the 2-back level can be seen in Figure 40 and 41.

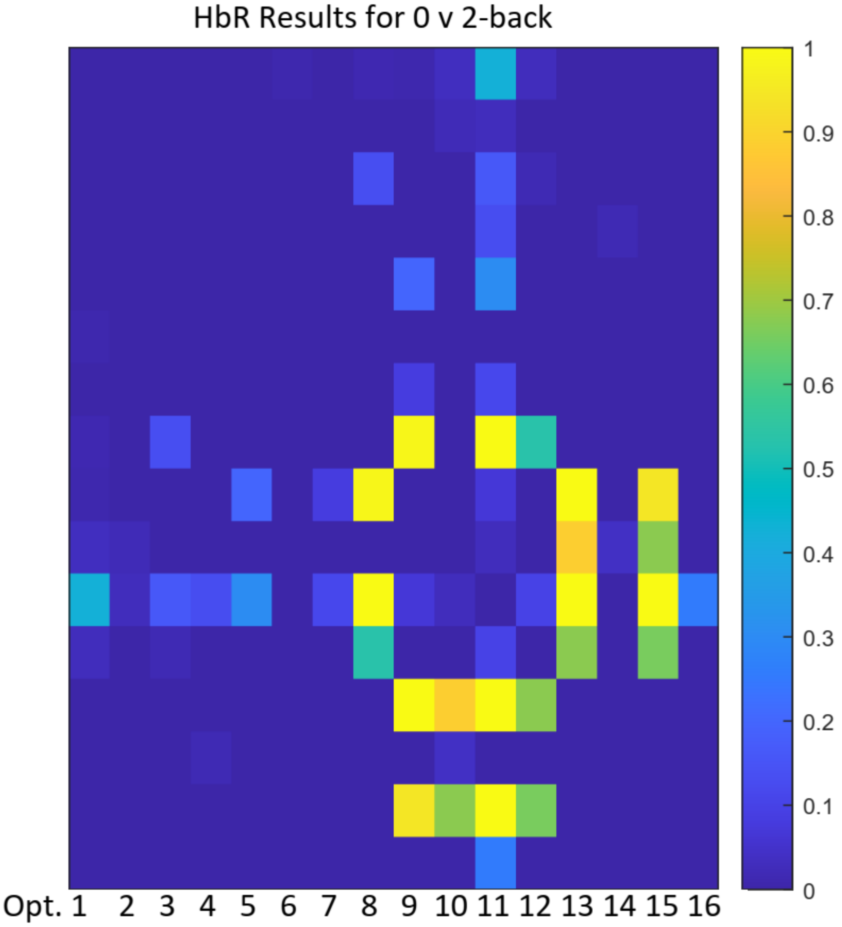


Figure 40: Significant results for the intrabrain comparison of 0-back and 2-back levels in HbR.

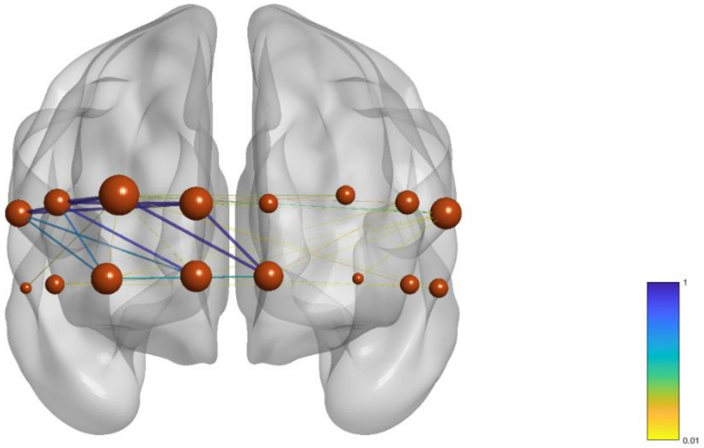


Figure 41: Topography of significant results for the intrabrain comparison of 0- and 2-back in HbR.

The result of comparing the 0-back level and the 3-back level can be seen in Figure 42 and 43.

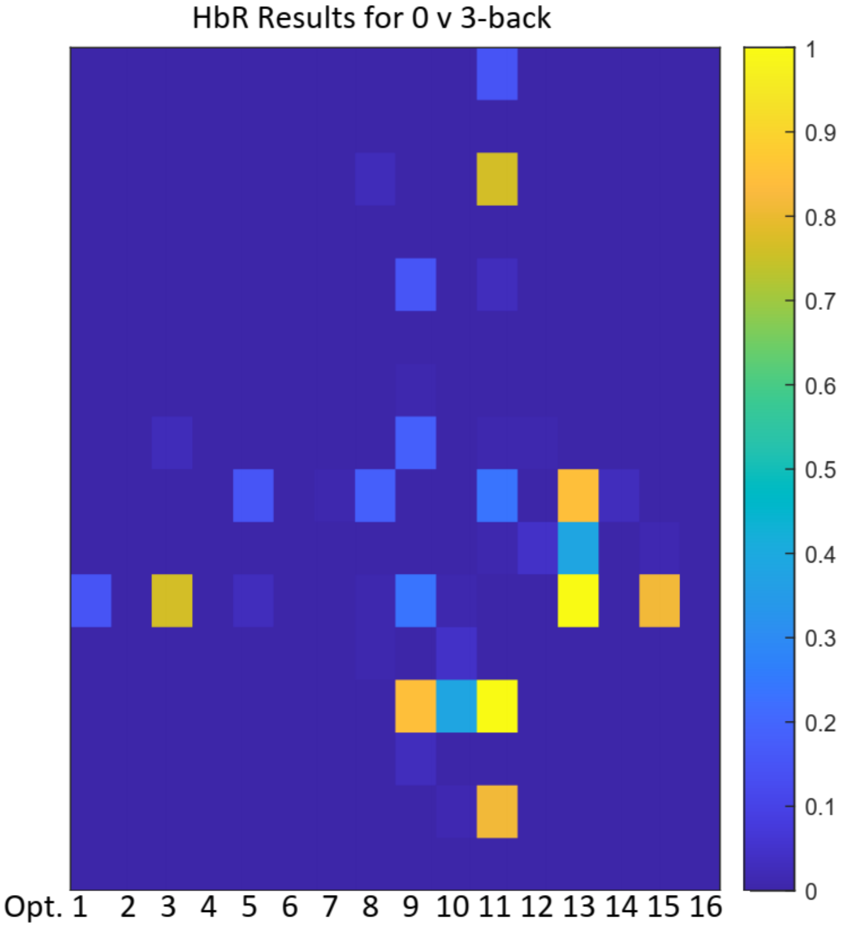


Figure 42: Significant results for the intrabrain comparison of 0-back and 3-back levels in HbR.

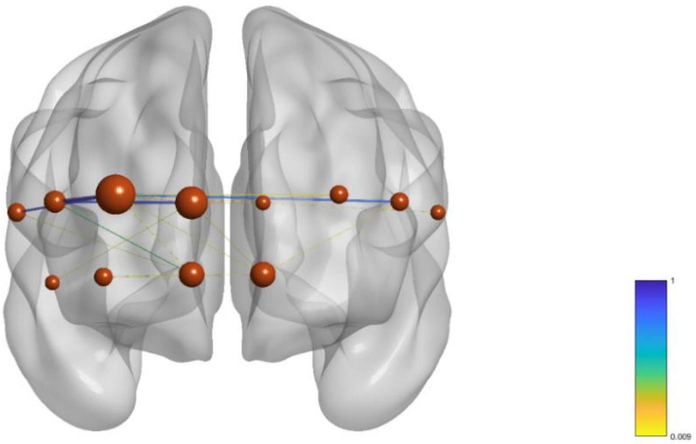


Figure 43: Topography of significant results for the intrabrain comparison of 0- and 3-back in HbR.

The result of comparing the 1-back level and the 2-back level can be seen in Figure 44 and 45.

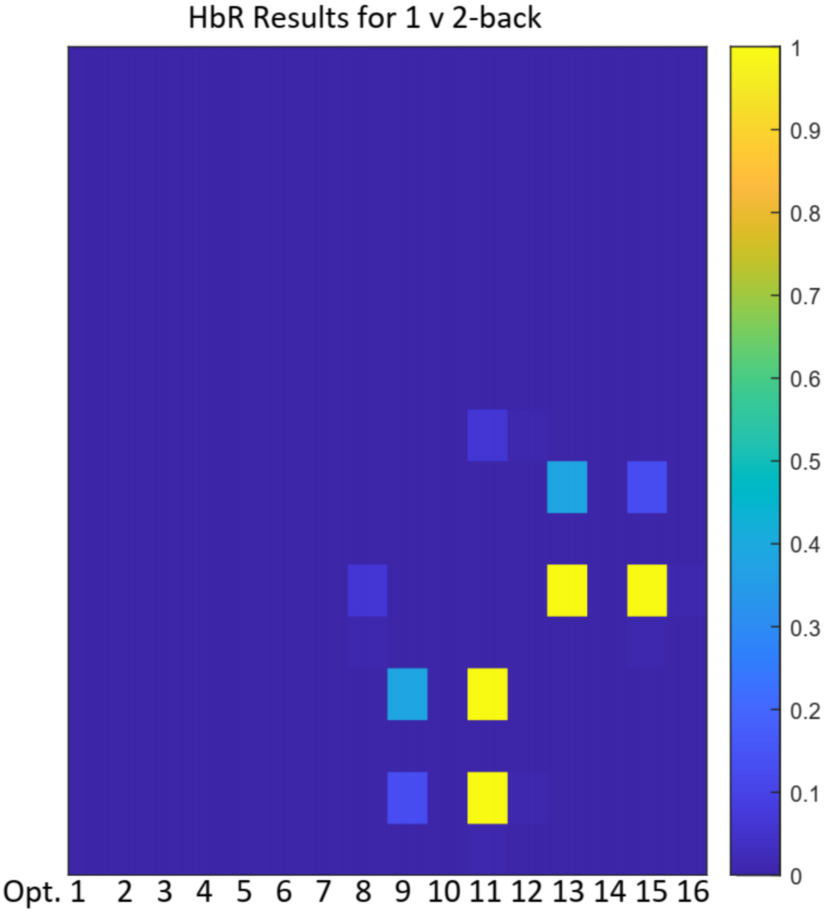


Figure 44: Significant results for the intrabrain comparison of 1-back and 2-back levels in HbR.

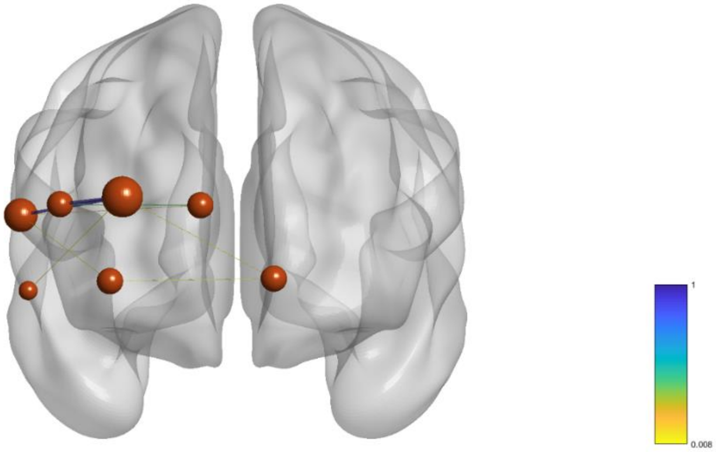


Figure 45: Topography of significant results for the intrabrain comparison of 1- and 2-back in HbR.

The result of comparing the 1-back level and the 3-back level can be seen in Figure 46 and 47.

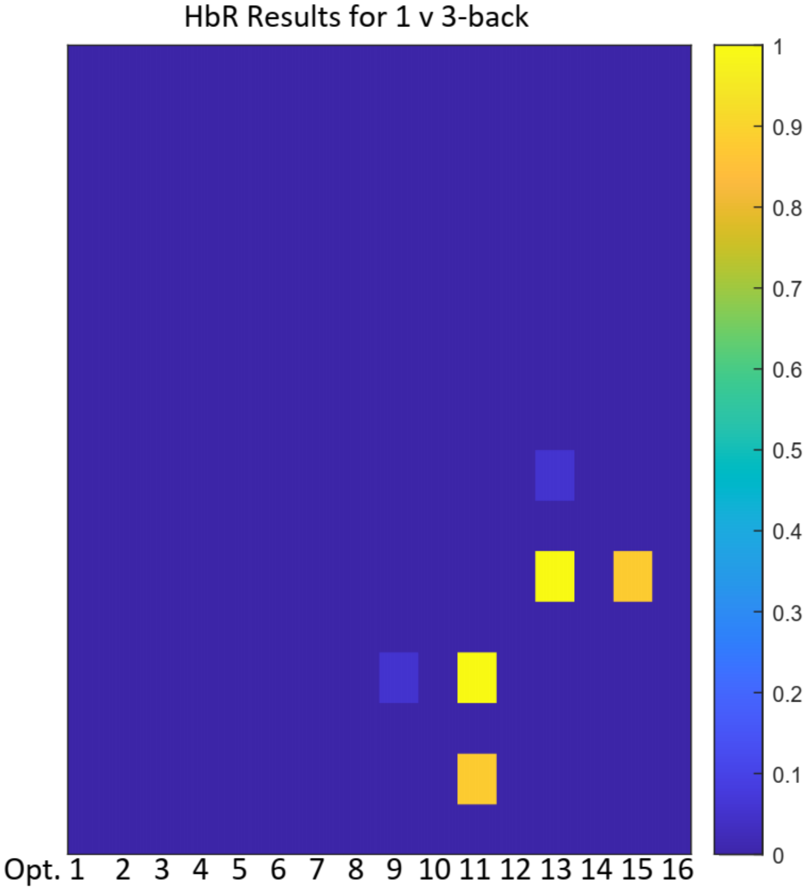


Figure 46: Significant results for the intrabrain comparison of 1-back and 3-back levels in HbR.

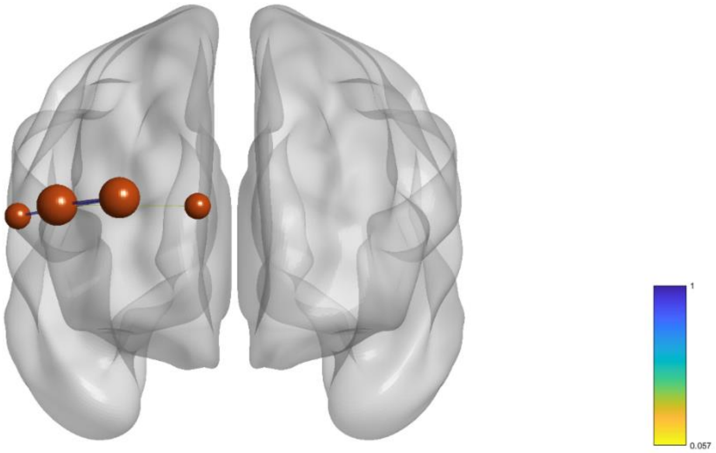


Figure 47: Topography of significant results for the intrabrain comparison of 1- and 3-back in HbR.

The result of comparing the 2-back level and the 3-back level can be seen in Figure Figure 48 and 49.

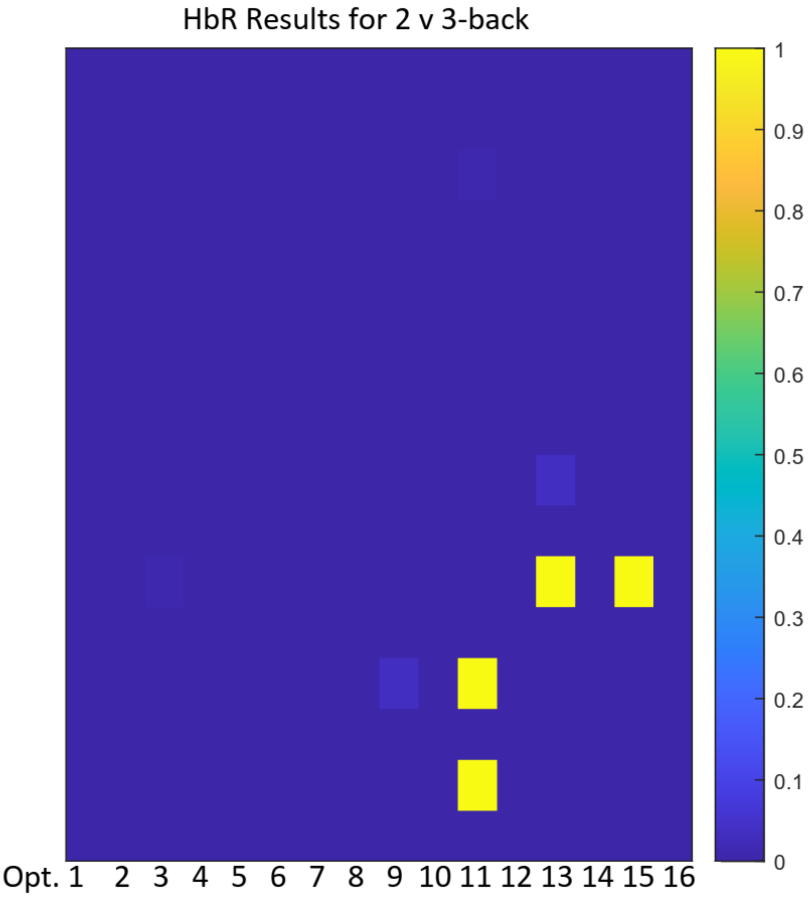


Figure 48: Significant results for the intrabrain comparison of 2-back and 3-back levels in HbR.

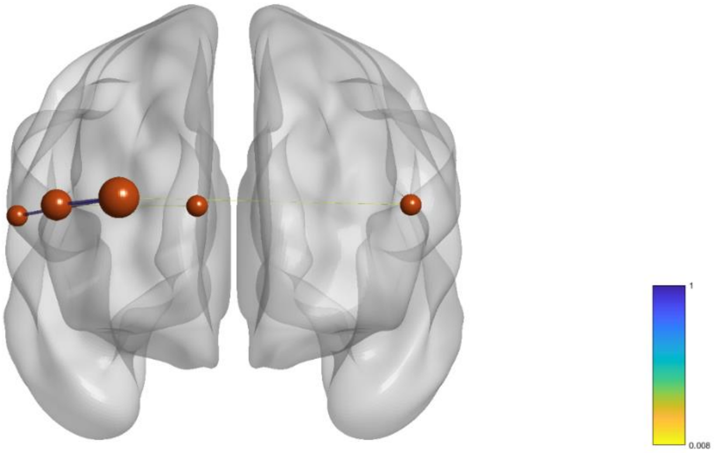


Figure 49: Topography of significant results for the intrabrain comparison of 2- and 3-back in HbR.

4.7. EEG Power Spectrum Analysis

Power spectrum analysis on EEG data was analyzed for the following comparisons: N-Back Levels and Social Setting of the Task in all participants' data, N-Back Levels and Social Setting of the Task in extravert participants' data, N-Back Levels and Social Setting of the Task in introvert participants' data, N-Back Levels and Extraversion Group during Individual Task Setting, N-Back Levels and Extraversion Group during Social Task Setting.

The analysis comparing n-back levels across all participants' data returned p-values lower than .01 in the Cz and Pz electrodes for the Theta band and not for other frequency bands. On the other hand, comparisons of social condition showed that EEG power was higher in the alone condition, however, p-values were not significant for any frequency band for the social setting. Please refer to Figures 50 to 52 for the topography plots. In the plots, Spectrum-1 means individual condition data and Spectrum-2 means social setting data, whereas the numbers next to them show the n-back level and frequency band of the plot.

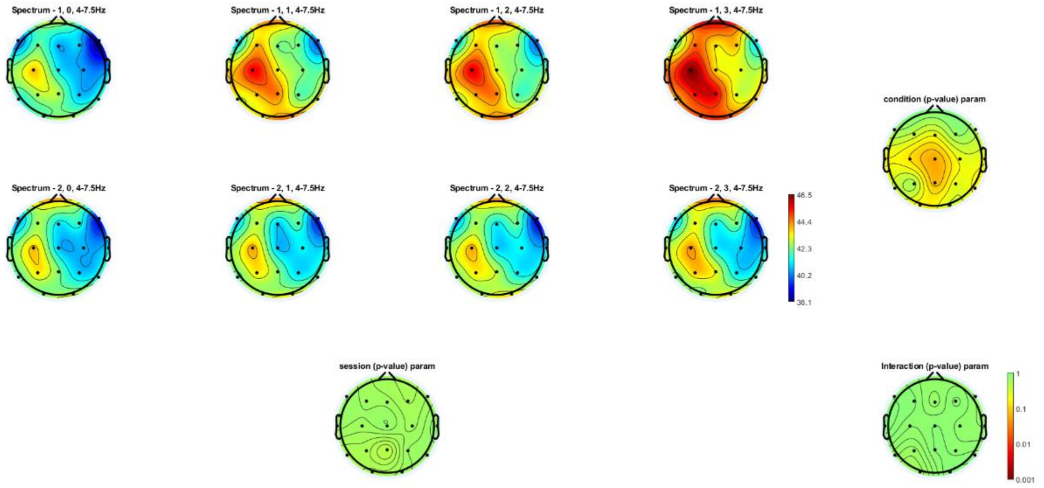


Figure 50: Results of EEG Power Spectrum Analysis in Theta band on n-back levels across all participants over social setting of the task. Spectrum-1 means individual condition data and Spectrum-2 means social setting data, whereas the numbers next to them show n-back level and frequency band of the plot.

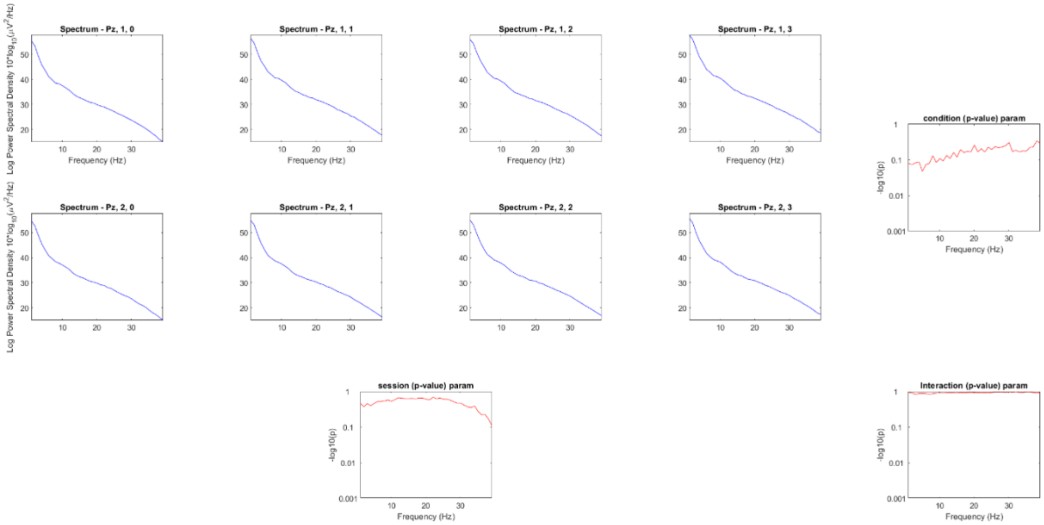


Figure 51: Results of EEG Power Spectrum Analysis on electrode Pz for n-back levels across all participants over social setting of the task. Spectrum-1 means individual condition data and Spectrum-2 means social setting data, whereas the numbers next to them show n-back level and electrode.

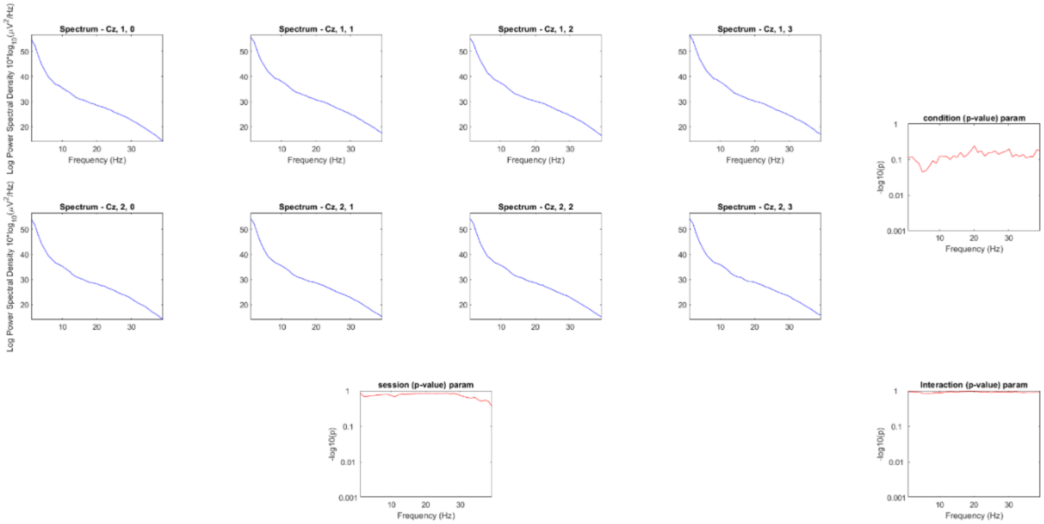


Figure 52: Results of EEG Power Spectrum Analysis on electrode Cz for n-back levels across all participants over social setting of the task. Spectrum-1 means individual condition data and Spectrum-2 means social setting data, whereas the numbers next to them show n-back level and electrode.

When the same comparison was conducted over data from only extravert participants, the results are similar that even though the EEG power seems to be higher during individual setting, p-values are not significant. The effect of n-back level is once again observed in electrodes C4, P4, and Pz, within frequency bands of Theta, Beta and Gamma. Please refer to Figures 53 to 58 for the visualizations. In the plots, Spectrum-1 means individual condition data and Spectrum-2 means social setting data, whereas the numbers next to them show n-back level and frequency band of the plot.

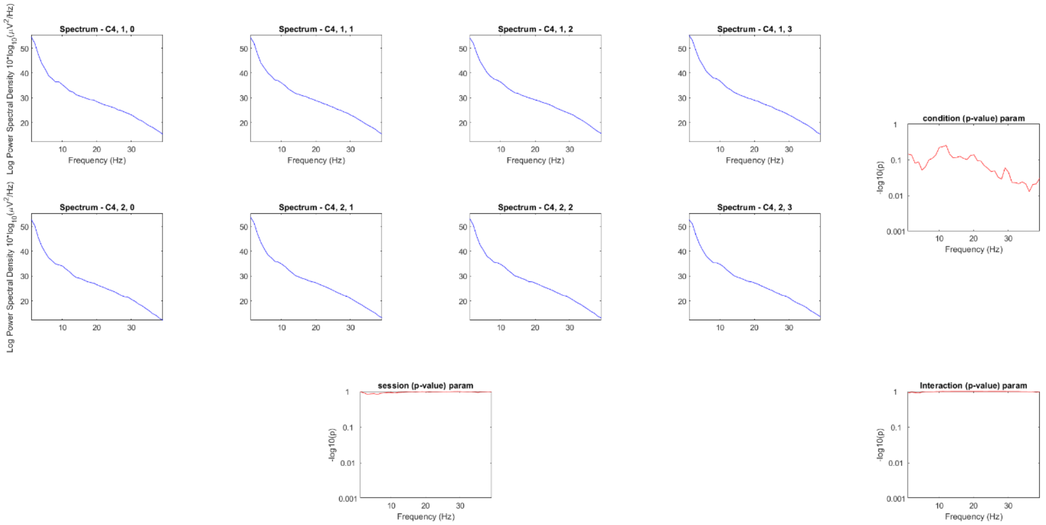


Figure 53: Results of EEG Power Spectrum Analysis on electrode C4 for n-back levels across extravert participants over social setting of the task. Spectrum-1 means individual condition data and Spectrum-2 means social setting data, whereas the numbers next to them show n-back level and electrode.

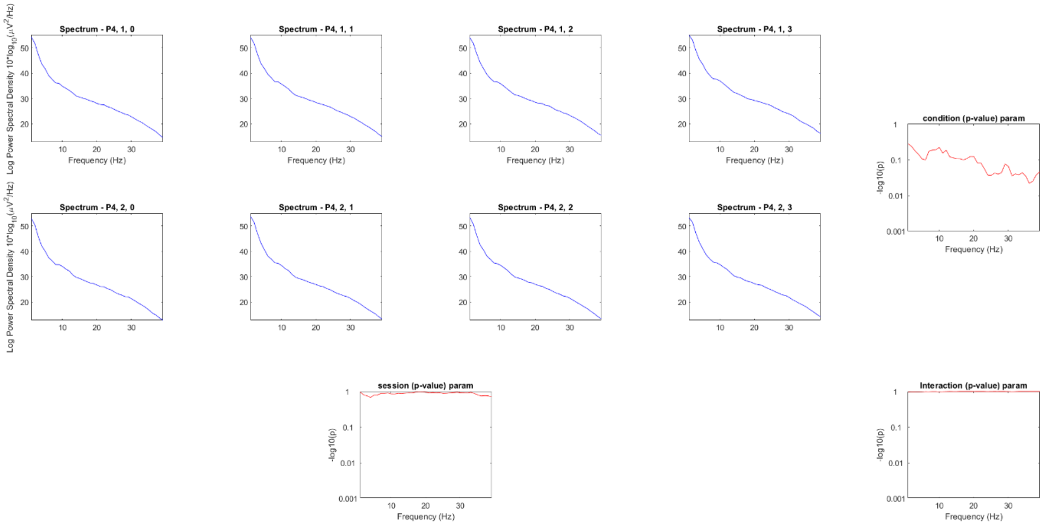


Figure 54: Results of EEG Power Spectrum Analysis on electrode P4 for n-back levels across extravert participants over social setting of the task. Spectrum-1 means individual condition data and Spectrum-2 means social setting data, whereas the numbers next to them show n-back level and electrode.

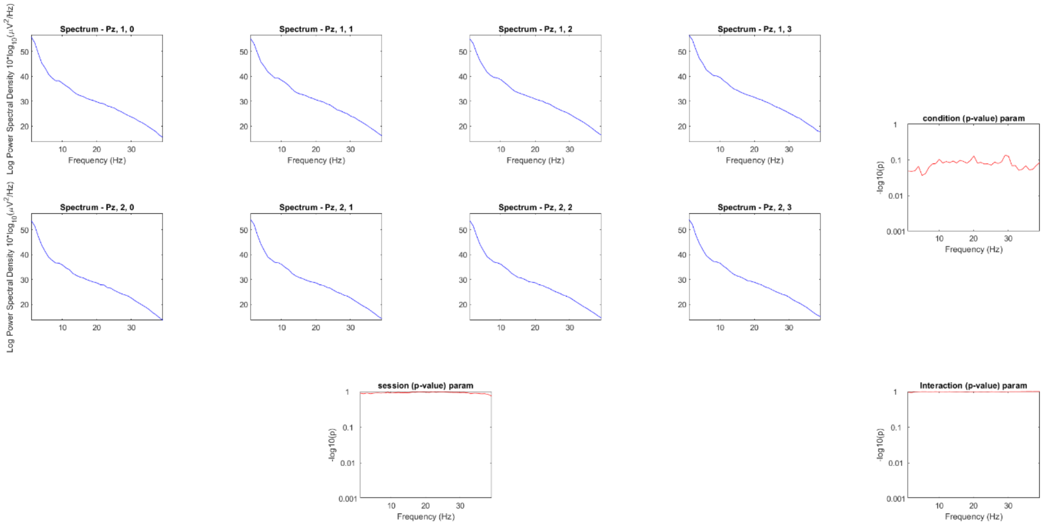


Figure 55: Results of EEG Power Spectrum Analysis on electrode Pz for n-back levels across extravert participants over social setting of the task. Spectrum-1 means individual condition data and Spectrum-2 means social setting data, whereas the numbers next to them show n-back level and electrode.

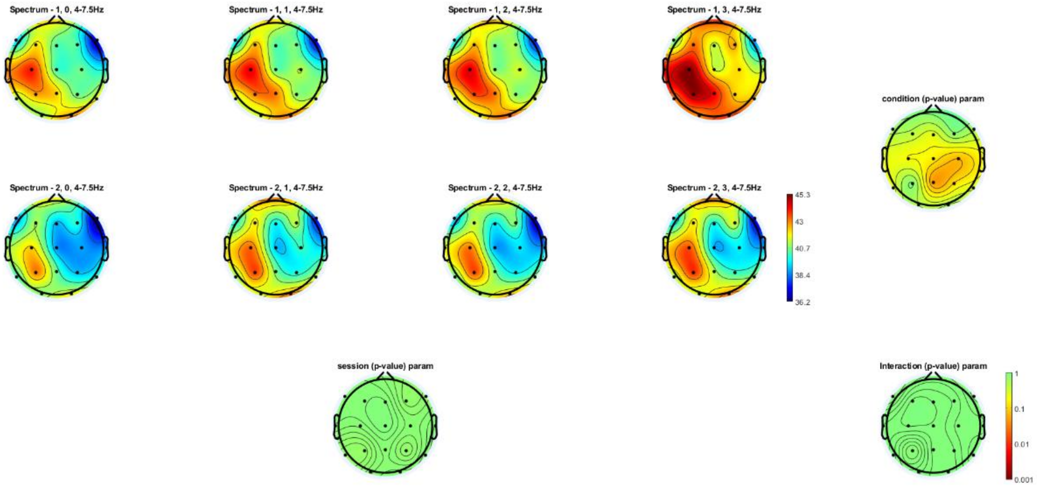


Figure 56: Results of EEG Power Spectrum Analysis in Theta band on n-back levels across extravert participants over social setting of the task. Spectrum-1 means individual condition data and Spectrum-2 means social setting data, whereas the numbers next to them show n-back level and frequency band of the plot.

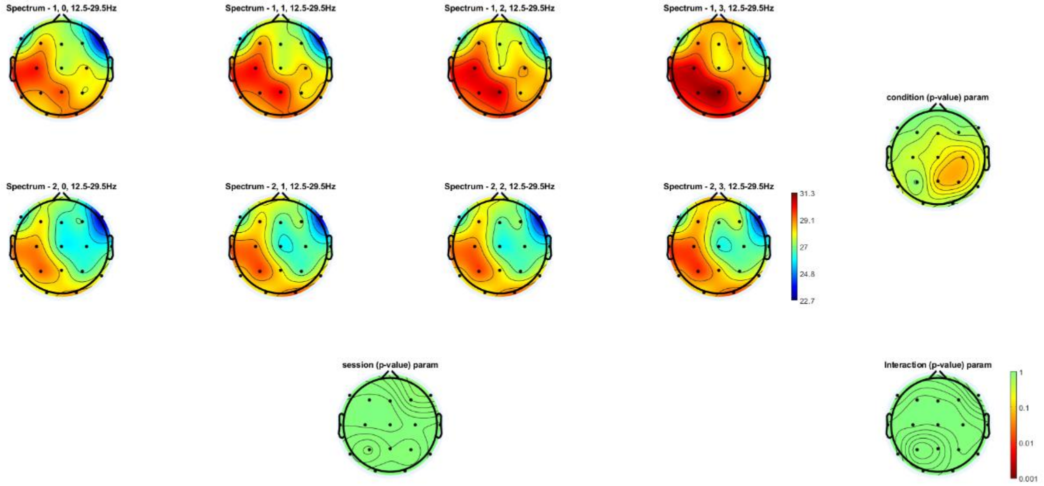


Figure 57: Results of EEG Power Spectrum Analysis in Beta band for n-back levels across extravert participants over social setting of the task. Spectrum-1 means individual condition data and Spectrum-2 means social setting data, whereas the numbers next to them show n-back level and frequency band of the plot.

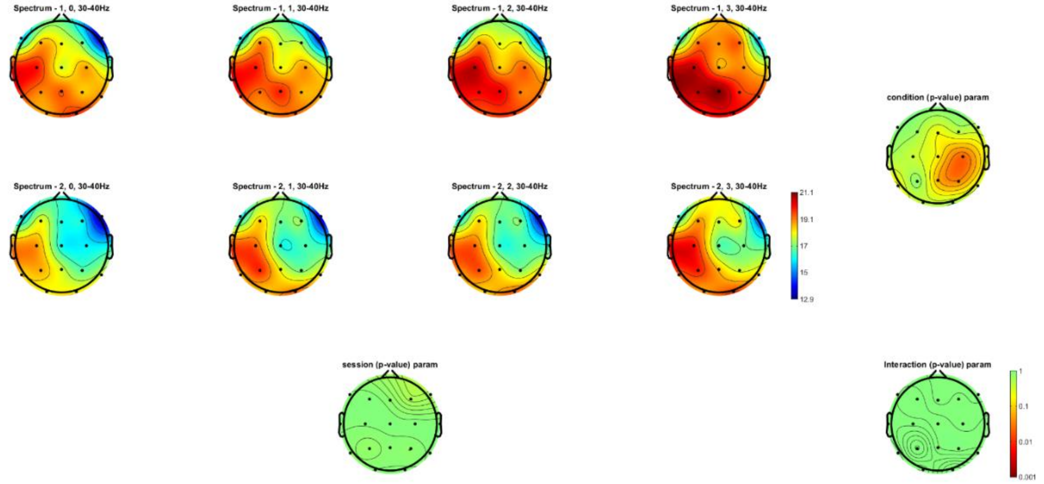


Figure 58: Results of EEG Power Spectrum Analysis in Gamma band for n-back levels across extravert participants over social setting of the task. Spectrum-1 means individual condition data and Spectrum-2 means social setting data, whereas the numbers next to them show n-back level and frequency band of the plot.

Repeating the same comparison on data from only introvert participants did not result in any significant differences.

Comparisons of n-back levels over extraversion groups were also conducted in order to observe whether different social conditions result in different outcomes. When only data from social session was analyzed, EEG power spectrum analysis revealed several electrodes with significant differences across frequency bands regarding the comparison of n-back levels. None of the p-values were significant for comparisons regarding extraversion but in general, EEG power was higher for extravert participants. Please refer to Figures 59 to 64 for visualizations. In the figures below, Spectrum-1 means introvert participants' data and Spectrum-2 means extravert participants' data, whereas the numbers next to them show n-back level and frequency band of the plot.

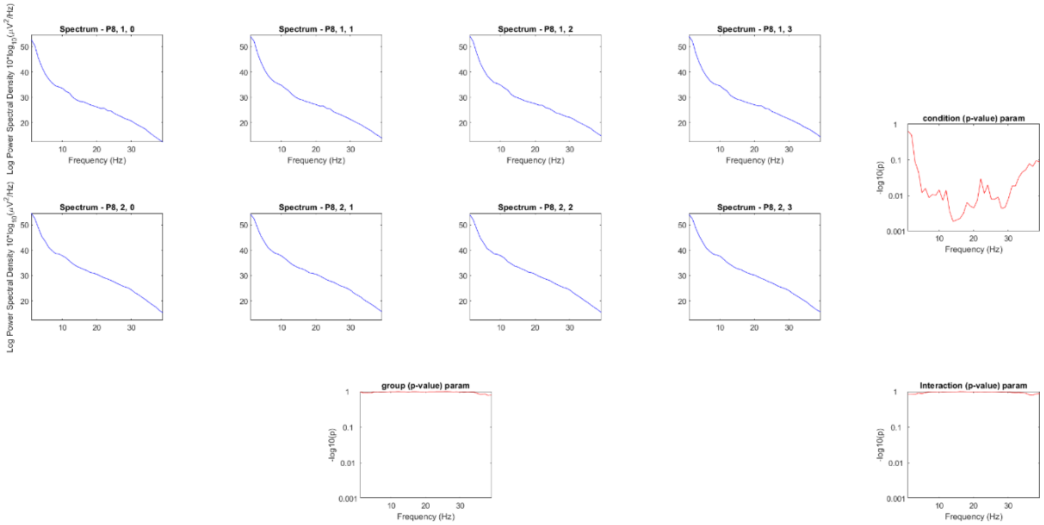

Spectrum - P8, 1, 0
Spectrum - P8, 1, 1
Spectrum - P8, 1, 2
Spectrum - P8, 1, 3
Spectrum - P8, 2, 0
Spectrum - P8, 2, 1
Spectrum - P8, 2, 2
Spectrum - P8, 2, 3
condition (p-value) param
group (p-value) param
Interaction (p-value) param

Figure 59: Results of EEG Power Spectrum Analysis on electrode P8 for n-back levels across all participants over extraversion in social setting. Spectrum-1 means introverts' data and Spectrum-2 means extraverts' data, whereas the numbers next to them show n-back level and electrode.

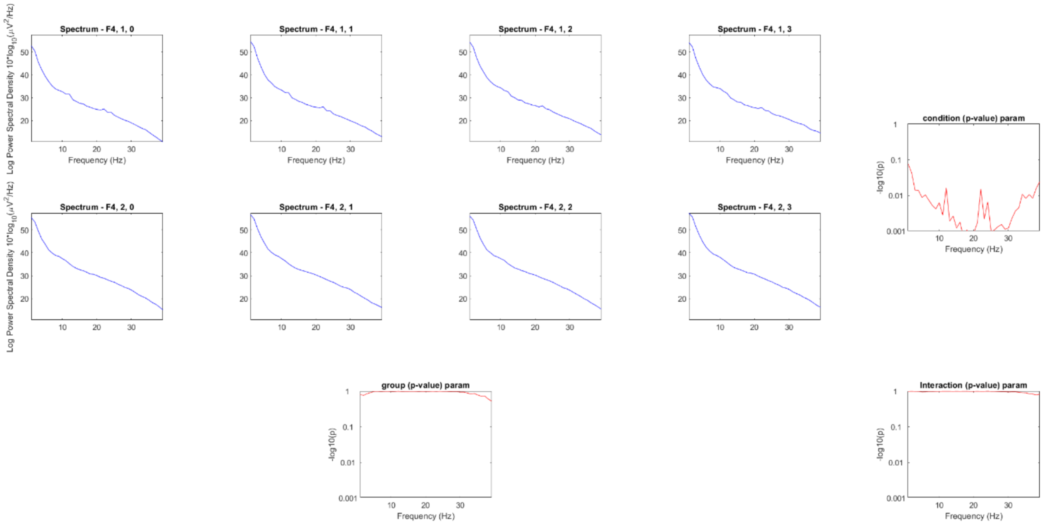

Spectrum - F4, 1, 0
Spectrum - F4, 1, 1
Spectrum - F4, 1, 2
Spectrum - F4, 1, 3
Spectrum - F4, 2, 0
Spectrum - F4, 2, 1
Spectrum - F4, 2, 2
Spectrum - F4, 2, 3
condition (p-value) param
group (p-value) param
Interaction (p-value) param

Figure 60: Results of EEG Power Spectrum Analysis on electrode F4 for n-back levels across all participants over extraversion in social setting. Spectrum-1 means introverts' data and Spectrum-2 means extraverts' data, whereas the numbers next to them show n-back level and electrode.

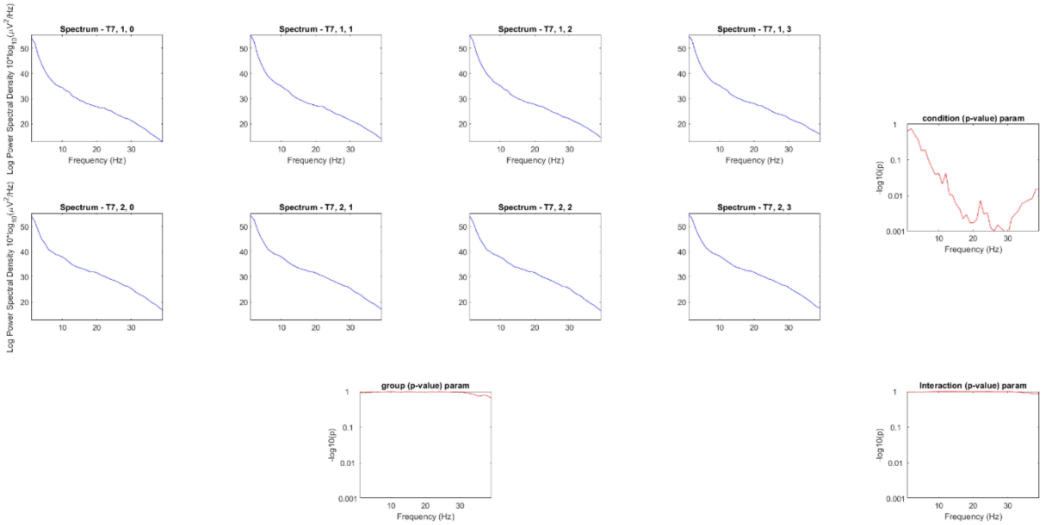


Figure 61: Results of EEG Power Spectrum Analysis on electrode T7 for n-back levels across all participants over extraversion in social setting. Spectrum-1 means introverts' data and Spectrum-2 means extraverts' data, whereas the numbers next to them show n-back level and electrode.

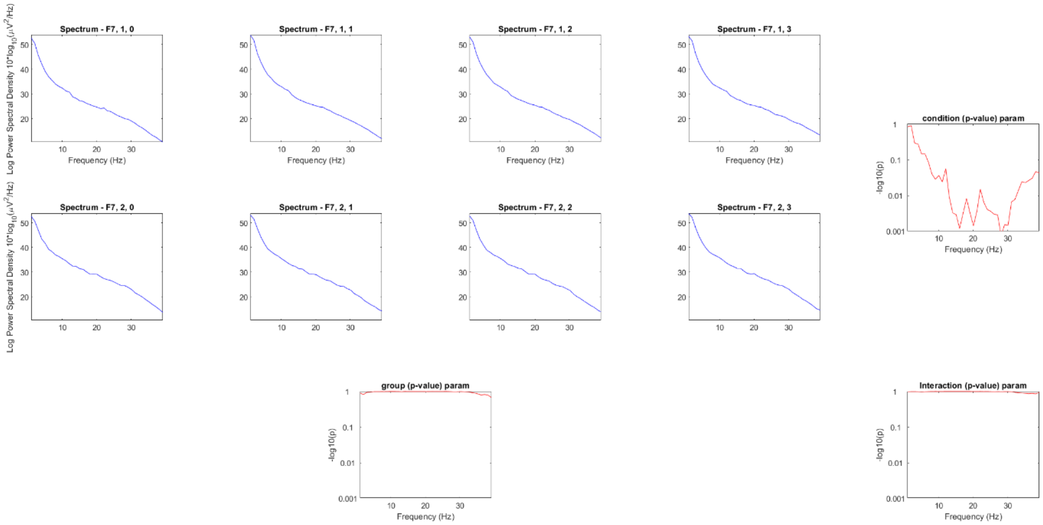


Figure 62: Results of EEG Power Spectrum Analysis on electrode F7 for n-back levels across all participants over extraversion in social setting. Spectrum-1 means introverts' data and Spectrum-2 means extraverts' data, whereas the numbers next to them show n-back level and electrode.

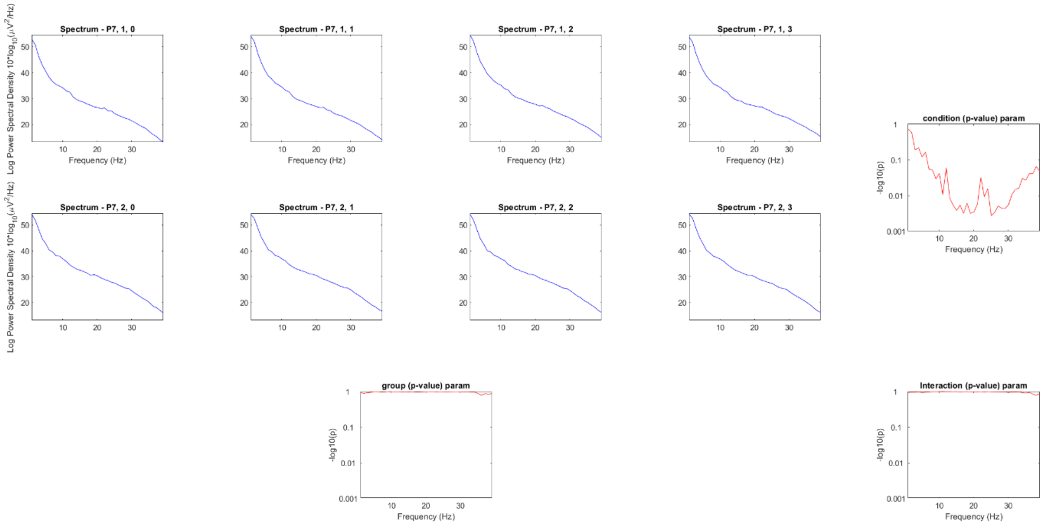


Figure 63: Results of EEG Power Spectrum Analysis on electrode P7 for n-back levels across all participants over extraversion in social setting. Spectrum-1 means introverts' data and Spectrum-2 means extraverts' data, whereas the numbers next to them show n-back level and electrode.

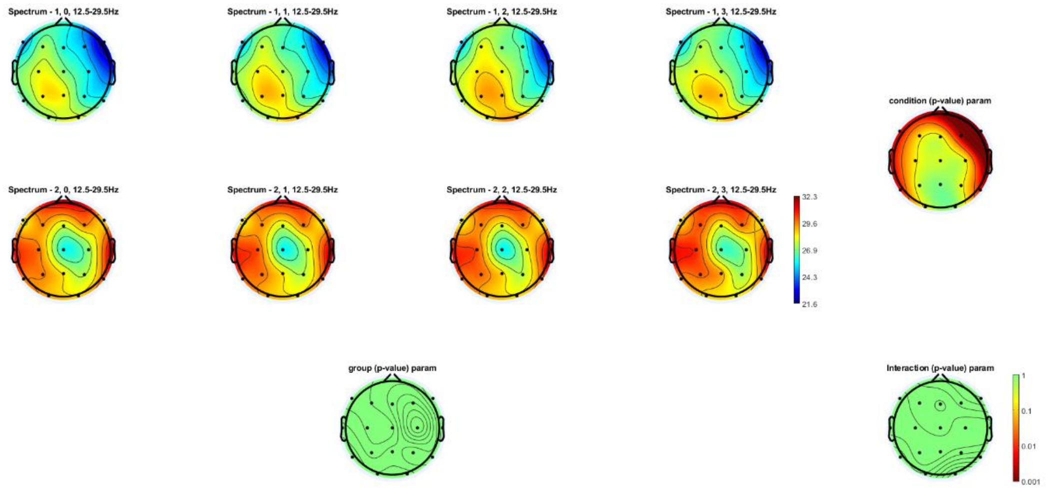


Figure 64: Results of EEG Power Spectrum Analysis in Beta band for n-back levels across all participants over extraversion in social setting. Spectrum-1 means introverts' data and Spectrum-2 means extraverts' data, whereas the numbers next to them show n-back level and frequency band of the plot.

The EEG power spectrum analysis over data from only individual task setting sessions showed that unlike social session data, fewer electrodes had significant p-values, and across fewer frequency bands regarding the comparison of n-back levels. None of the p-values were significant for comparisons regarding extraversion but in general, EEG power was higher for introvert participants. Please refer to Figures 65 to 67 for visualizations. In the figures below, Spectrum-1 means introvert participants' data and Spectrum-2 means extravert participants' data, whereas the numbers next to them show n-back level and frequency band of the plot.

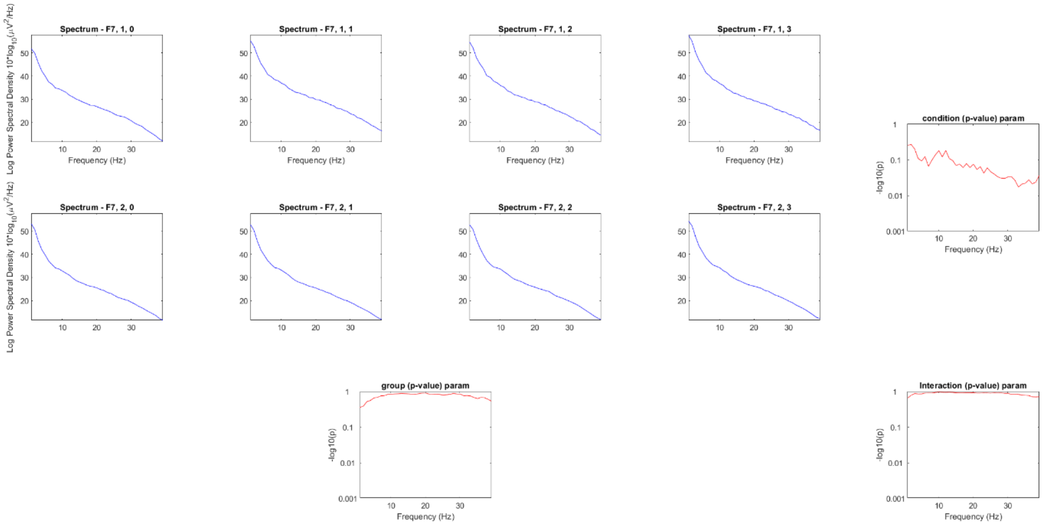


Figure 65: Results of EEG Power Spectrum Analysis on electrode F7 for n-back levels across all participants over extraversion in individual setting. Spectrum-1 means introverts' data and Spectrum-2 means extraverts' data, whereas the numbers next to them show n-back level and electrode.

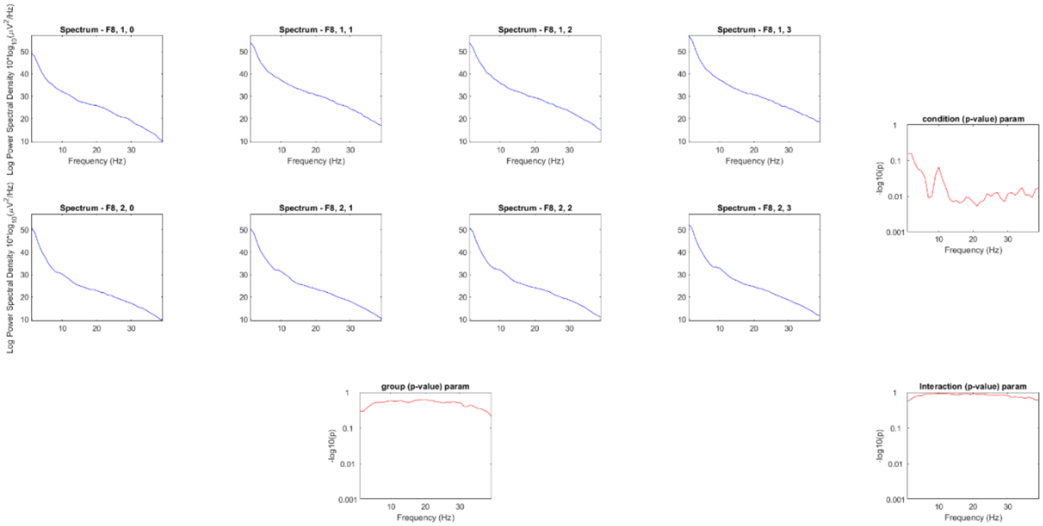


Figure 66: Results of EEG Power Spectrum Analysis on electrode F8 for n-back levels across all participants over extraversion in individual setting. Spectrum-1 means introverts' data and Spectrum-2 means extraverts' data, whereas the numbers next to them show n-back level and electrode.

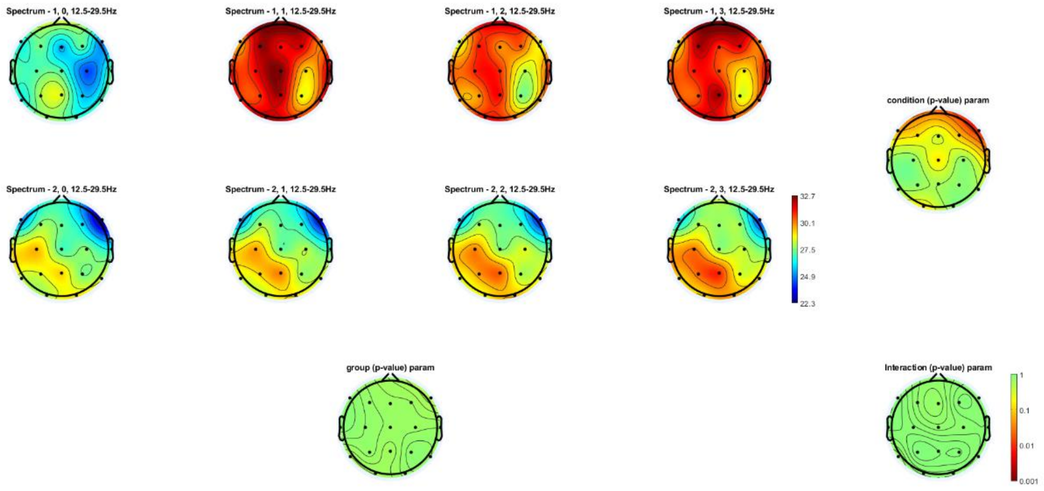


Figure 67: Results of EEG Power Spectrum Analysis in Beta band for n-back levels across all participants over extraversion in individual setting. Spectrum-1 means introverts' data and Spectrum-2 means extraverts' data, whereas the numbers next to them show n-back level and frequency band.

4.8. ERP Analysis

Since there are too many comparisons, only the tests which showed a significant effect will be presented in detail.

4.8.1. Comparisons Regarding Bins

At first, all comparisons regarding bins were conducted on data from all social conditions and all n-back levels regardless of TIPI. Tmax permutation tests were not significant in bin 3, 5, and 7.

In bin 1, Correct Response to Letter Target Stimulus, tmax permutation tests were significant in electrode T8 between 192 to 196 ms, and electrode F8 between 418-684 ms. with p-values between .0452 and .0032, *df* = 63, *t* = 3.7956 (Please see Figure 68).

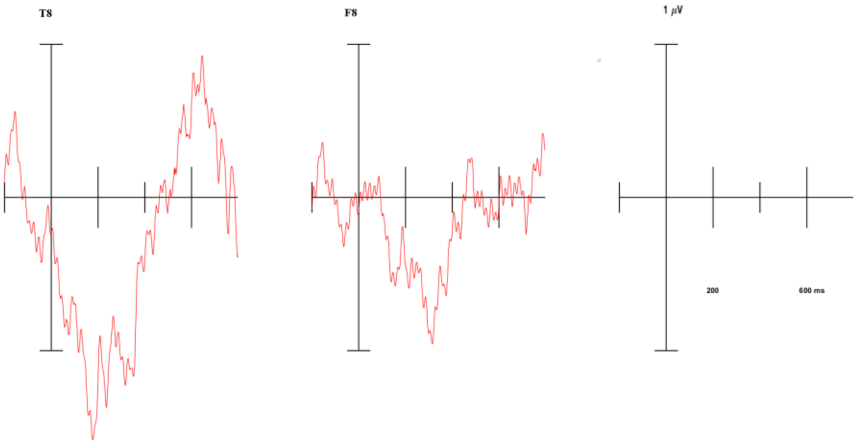


Figure 68: ERP for correct response for letter on T8 and F8, the figure on right shows axis values.

In bin 2, Correct Response to Place Target Stimulus, tmax permutation test was significant in electrode Fz between 366-660 ms. with p-values between .0496 and 0, *df* = 59, *t* = 3.649 (Please see Figure 69).

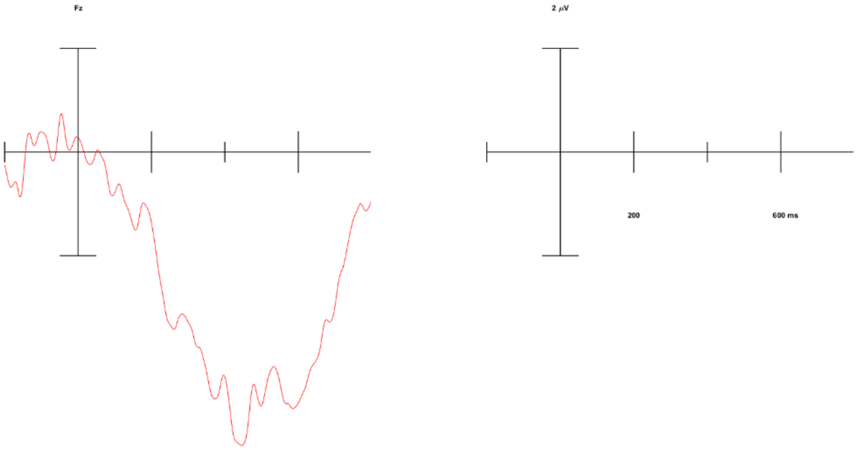


Figure 69: ERP for correct response for place on Fz, the figure on right shows axis values.

In bin 4, Missed Trial, tmax permutation test was significant in electrode O1 between 292-294 ms and O2 between 242-280 ms. with p-values between .0476 and .01, *df* = 82, *t* = 3.7821 (Please see Figure 70).

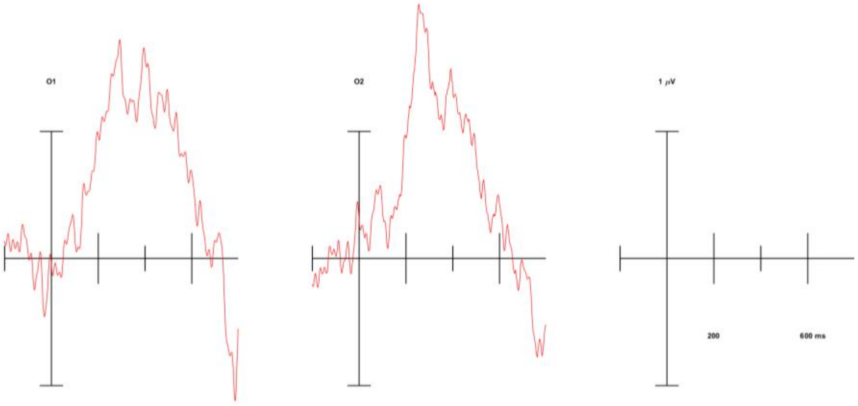


Figure 70: ERP for missed trial on O1, the figure on right shows axis values.

In bin 6, Wrong Response to Letter Target Stimulus, tmax permutation tests were significant in electrode O2 between 312-350 ms. with p-values between .0488 and .0036, *df* = 25, *t* = 3.9945 (Please see Figure 71).

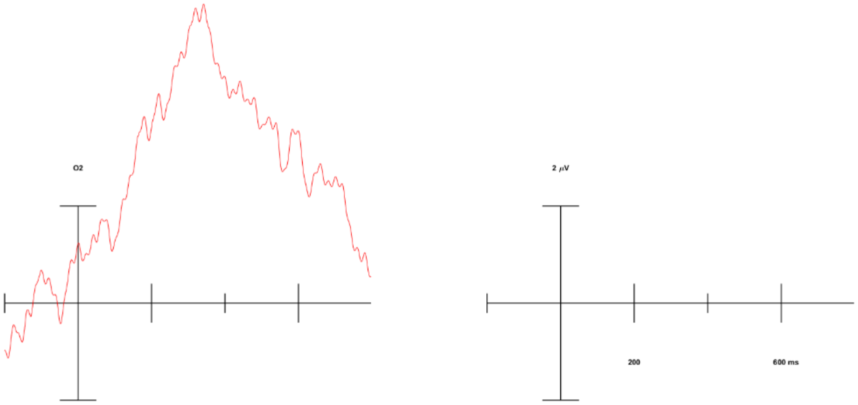


Figure 71: ERP for wrong response to letter on O2, the figure on right shows axis values.

4.8.2. Comparisons Regarding n-Back Level

Comparisons of each n-back level were analyzed for any difference in ERP values without regard to social setting of the task or extraversion scores. Comparisons of 1-back vs. 2-back, 1-back vs. 3-back, and 2-back vs. 3-back did not yield significant effects.

The comparison of 0-back to 1-back showed a significant effect on Correct Response to Non-Target Stimulus in electrode O1 between 604 and 740 ms with p-values between .0464 and .0032, *df* = 167, *t* = 3.835 (Please see Figure 72). Other bins were not significant.

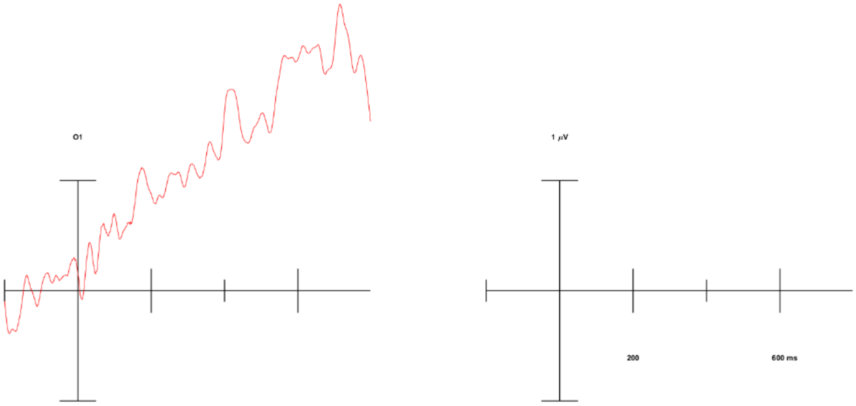


Figure 72: ERP for correct no response on O1 between all participants in 0- and 1-back, the figure on right shows axis values.

The comparison of 0-back to 2-back showed a significant effect on Correct Response to Non-Target Stimulus in electrode O1 between 616 and 660 ms with p-values between .0456 and .0264, *df* = 168, *t* = 3.8213; on Wrong Response to Non-Target Stimulus in electrode C4 between 648 and 792 ms with p-values between .0496 and 0, *df* = 61, *t* = 3.9376; on Wrong Response to Letter Target Stimulus in electrode F3 between 428 and 462 ms with p-values between .0492 and .0276, *df* = 46, *t* = 4.6938 (Please see Figures 73 to 75). Other bins were not significant.

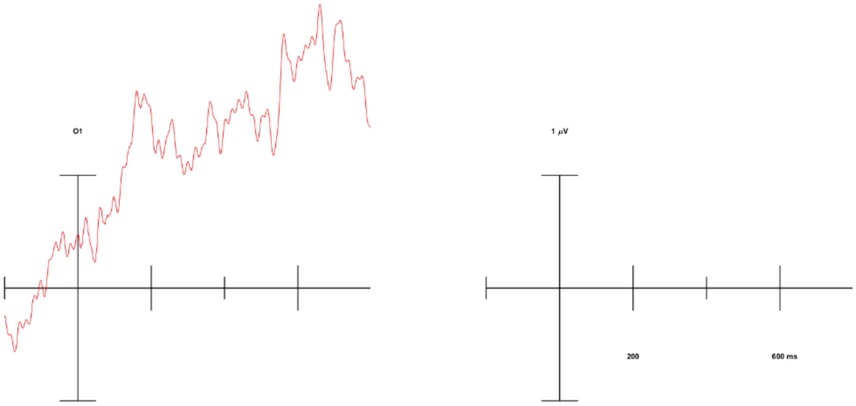


Figure 73: ERP for correct no response on O1 between all participants in 0- and 2-back, the figure on right shows axis values.

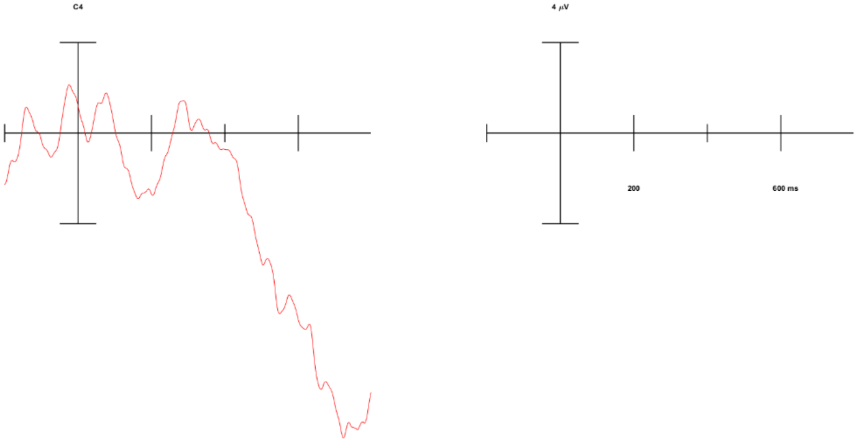


Figure 74: ERP for wrong response to non-target on C4 between all participants in 0- and 2-back, the figure on right shows axis values.

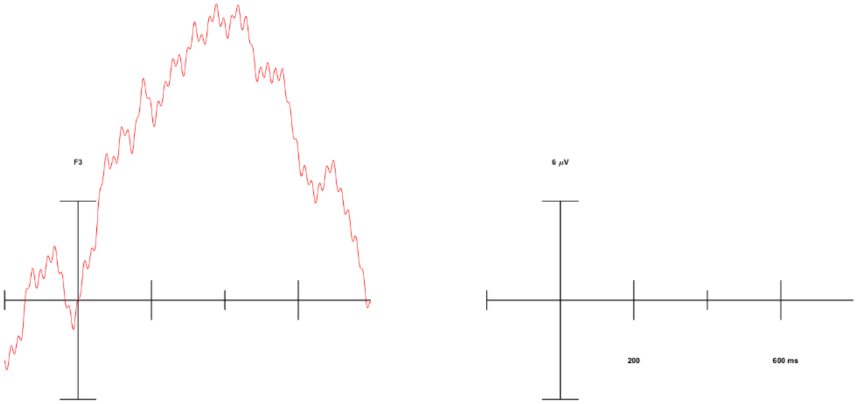


Figure 75: ERP for wrong response to letter on F3 between all participants in 0- and 2-back, the figure on right shows axis values.

The comparison of 0-back to 3-back showed a significant effect on Correct Response to Letter Target Stimulus in electrode T8 between 176 - 360 ms and P8 between 334 - 358 ms with p-values between .0476 and .0012, *df* = 123, *t* = 3.7388; on Wrong Response to Non-Target Stimulus in electrode C4 between 692 and 792 ms with p-values between .0496 and .0068, *df* = 47, *t* = 4.0316 (Please see Figures 76 and 77). Other bins were not significant.

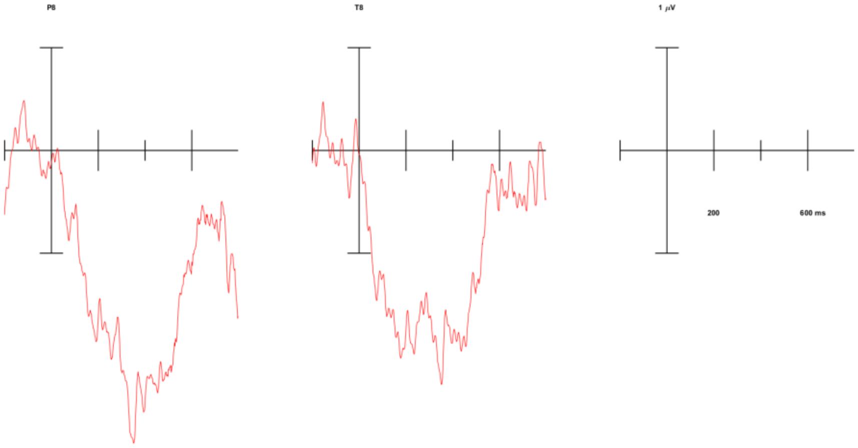


Figure 76: ERP for correct response to letter on P8 between all participants in 0- and 3-back, the figure on right shows axis values.

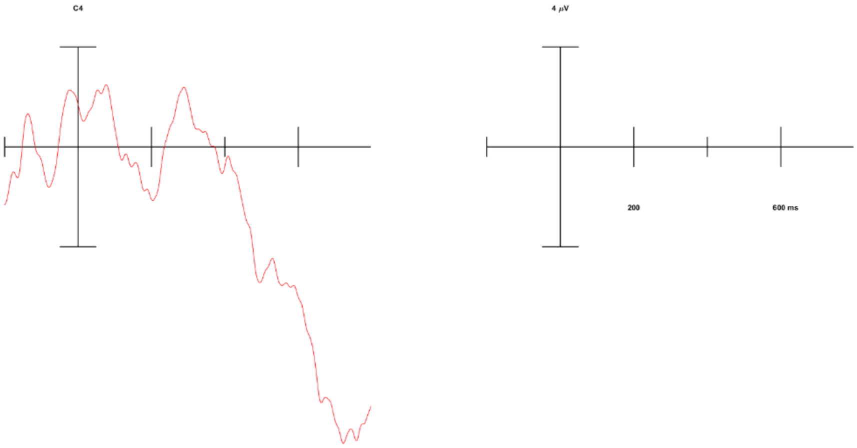


Figure 77: ERP for wrong response to non-target on C4 between all participants in 0- and 3-back, the figure on right shows axis values.

4.8.3. Comparisons Regarding Social Setting of the Task

ERP data from the individual condition and the social condition were compared across n-back levels regardless of TIPI values for these analyses. The comparison of individual and social sessions did not yield significant effects over any event type in 0-back, 2-back, and 3-back.

The comparison of individual condition data to social condition data during 1-back showed a significant effect on Missed Trial in electrode T8 between 210 and 266 ms and electrode P8 between 512 and 520 ms with p-values between .0468 and .0032, *df* = 67, *t* = 3.7248; on Wrong Response to Non-Target Stimulus in electrode P4 between 744 and 766 ms and electrode P7 between 762 - 766 ms with p-values between .0496 and .0144, *df* = 17, *t* = 4.4489 (Please see Figures 78 and 79). Other bins were not significant.

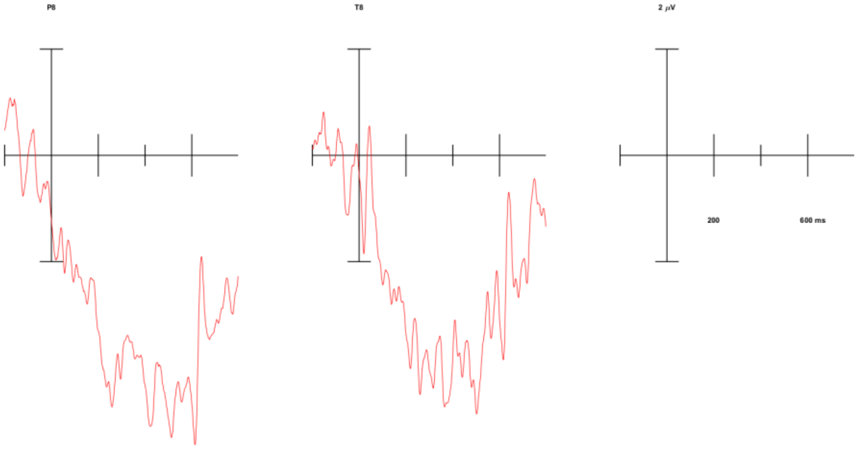


Figure 78: ERP for missed trial on P8 and T8 on 1-back over task setting, the figure on right shows axis values.

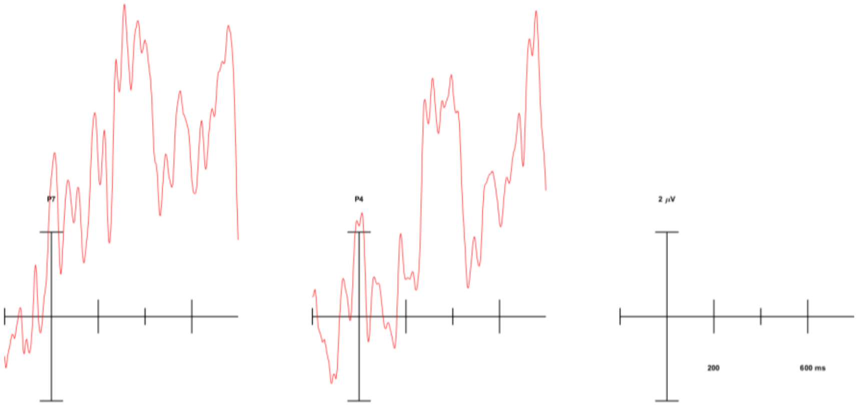


Figure 79: ERP for wrong response to non-target on P7 and P4 on 1-back over task setting, the figure on right shows axis values.

Additionally, n-back level comparisons were applied over only individual session data and only social session data. There were no significant effects in social session data for 1-back vs. 2-back, 1-back vs. 3-back, 2-back vs. 3-back in either task type. For individual task type, there were no effects in any n-back level.

The comparison of 0-back to 1-back in social session data showed a significant effect on Correct Response to Non-Target Stimulus in electrode P8 between 744 and 752 ms with p-values between .048 and .0428, *df* = 84, *t* = 3.8126 (Please see Figure 80). Other bins were not significant.

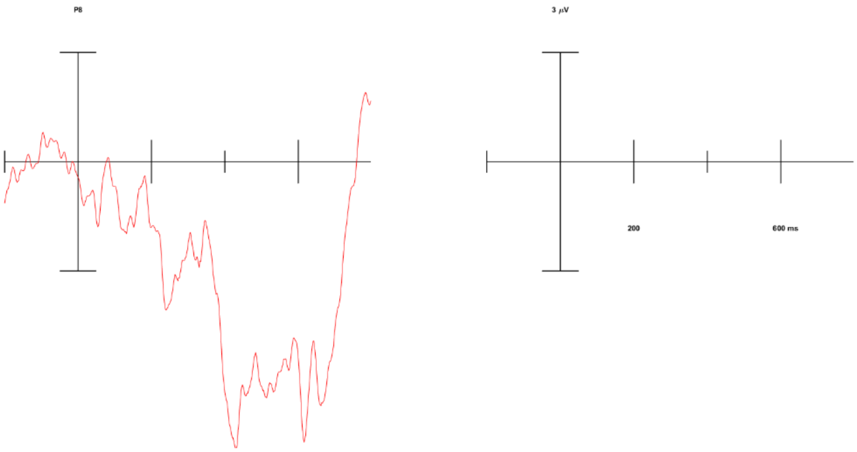


Figure 80: ERP for missed trial on P8 on social session between 0- and 1-back, the figure on right shows axis values.

The comparison of 0-back to 2-back in social session data showed a significant effect on Correct Response to Letter Stimulus in electrode P8 between 580 and 586 ms with p-values between .048 and .0428, *df* = 86, *t* = 3.8178; and on Wrong Response to Non-Target Stimulus in electrode C4 between 612 and 754 ms with p-values between .0468 and .0008, *df* = 40, *t* = 4.0102 (Please see Figures 81 and 82). Other bins were not significant.

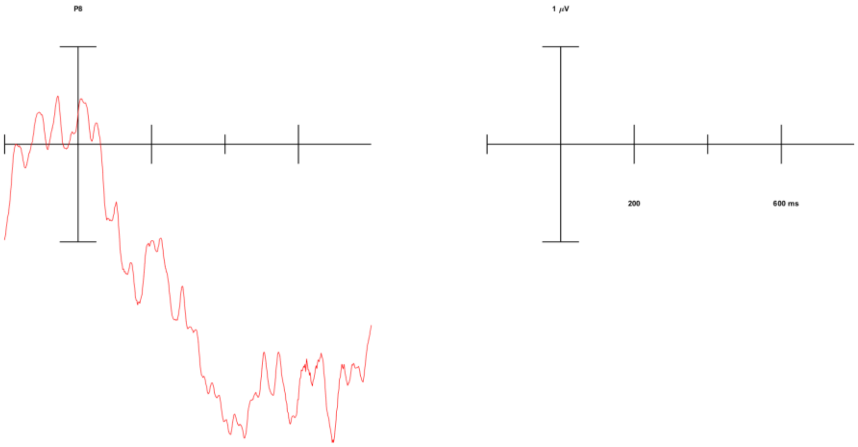


Figure 81: ERP for correct response to letter on P8 on social session between 0- and 2-back, the figure on right shows axis values.

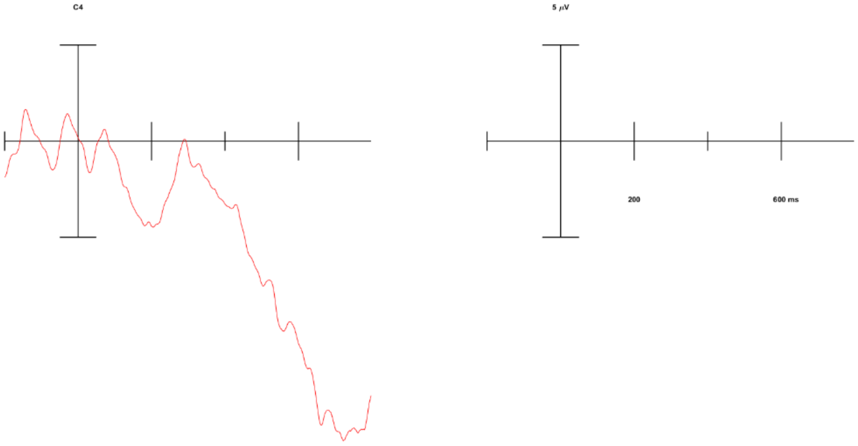


Figure 82: ERP for wrong response to non-target on C4 on social session between 0- and 2-back, the figure on right shows axis values.

The comparison of 0-back to 3-back in social session data showed a significant effect on Correct Response to Letter Stimulus in electrode T8 between 352 and 354 ms, and electrode F8 between 376-378 ms with p-values between 0.0476 and 0.0436, *df* = 83, *t* = 3.7676 (Please see Figure 83). Other bins were not significant.

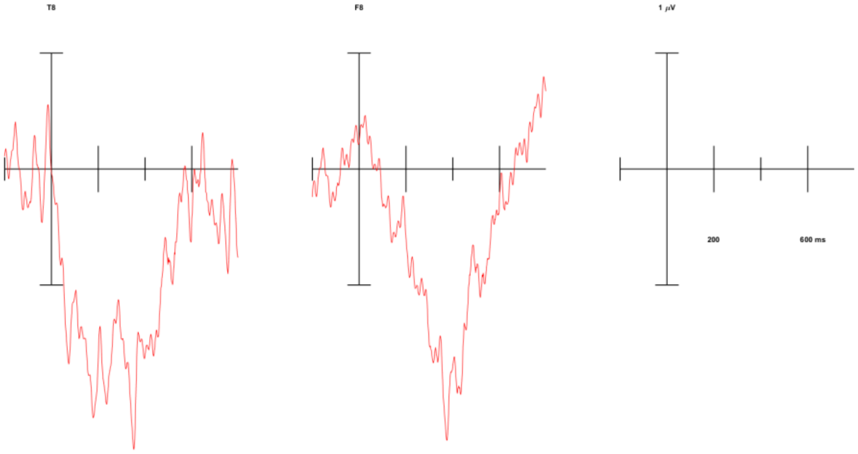


Figure 83: ERP for correct response to letter on T8 and F8 on social session between 0- and 3-back, the figure on right shows axis values.

4.8.4. Comparisons Regarding Extraversion

The analyses comparing data from extravert participants and introvert participants were conducted for comparisons of n-back levels as well as comparisons of individual session data to social session data. There were no significant effects on any event types for neither extraverts nor introverts in the comparisons of individual data vs. social data on 0-back data or 3-back data. The comparison of individual data vs. social data on 2-back did not yield any significant effects on extraverts.

The comparison of individual setting data to social setting data in 1-back level for only extravert participants' data showed a significant effect on Missed Trial in electrode T8 between 480 and 490 ms with p-values between .0476 and .0304, *df* = 38, *t* = 3.8239; and on Wrong Response to Non-Target stimulus in electrode P7 between 378-382 ms, and electrode P4 between 740-752 ms with p-values between .0444 and .0208, *df* = 10, *t* = 5.2619 (Please see Figures 84 and 85). Other bins were not significant.

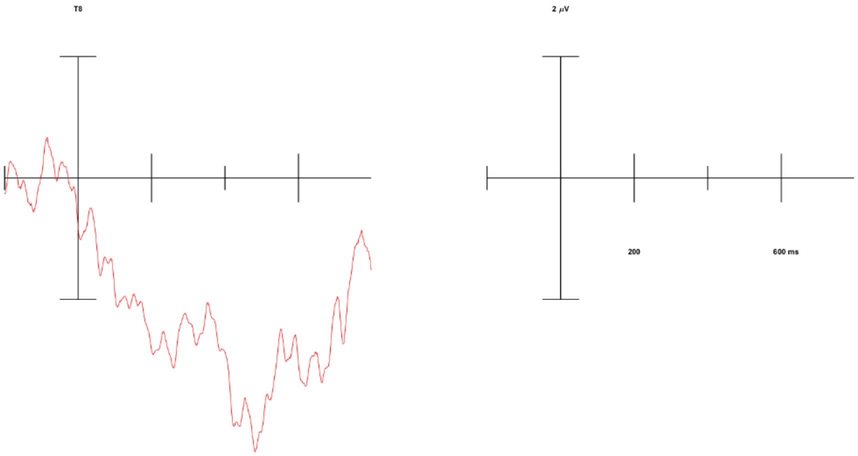


Figure 84: ERP for missed trial on T8 on extraverts' 1-back over task setting, the figure on right shows axis values.

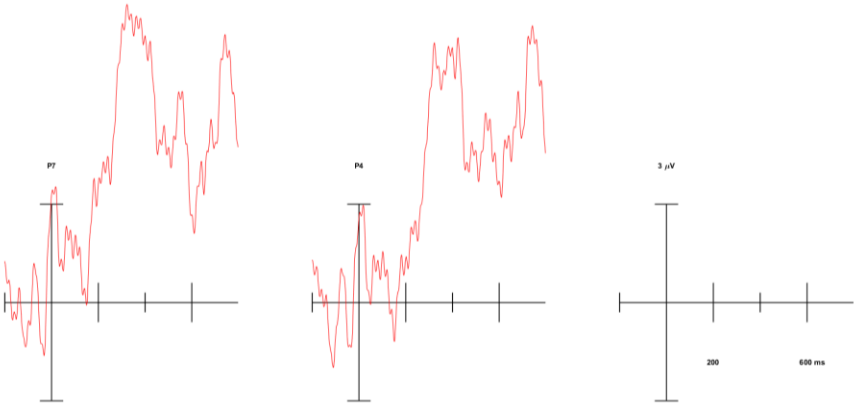


Figure 85: ERP for wrong response to non-target on P7 and P4 on extraverts' 1-back over task setting, the figure on right shows axis values.

The comparison of individual setting data to social setting data in 1-back level for only introvert participants' data showed a significant effect on Missed Trial in electrode F8 between 176-210 ms with p-values between .0496 and .0292, *df* = 16, *t* = 4.8073 (Please see Figure 86). Other bins were not significant.

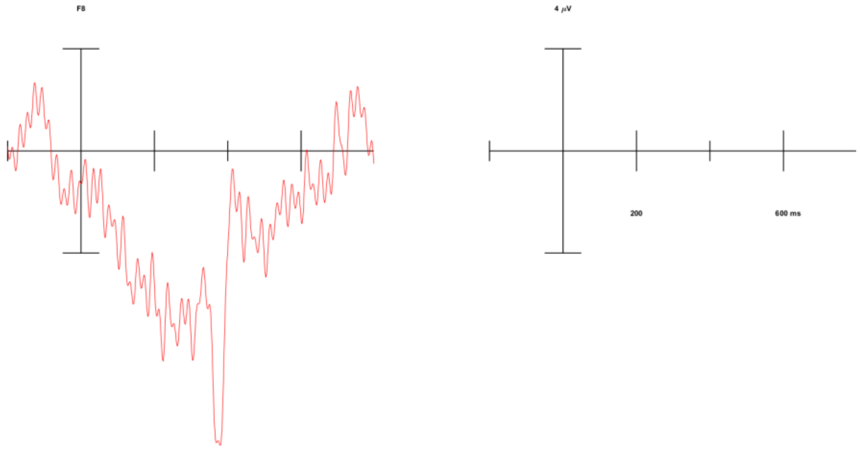


Figure 86: ERP for missed trial on F8 on introverts' 1-back over task setting, the figure on right shows axis values.

The comparison of individual to social setting in 2-back for only introvert participants' data showed a significant effect on Correct Response to Letter Stimulus in electrode O2 between 434-528 ms and O1 between 602-684 ms with p-values between .0476 and .0028, *df* = 18, *t* = 4.4944 (Please see Figure 87). Other bins were not significant.

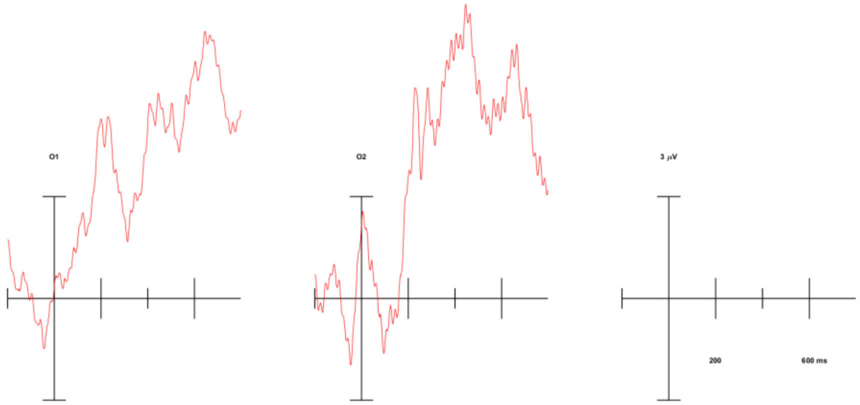


Figure 87: ERP for correct response to letter on O1 and O2 on introverts' 2-back over task setting, the figure on right shows axis values.

The only significant effect was on 3-back level individual task data when data from introverts and extraverts on the same n-back level and task setting was compared, other n-back levels on either task setting and 3-back level social task setting did not yield any significant results in any event type. The comparison of introverts to extraverts in 3-back individual session data showed a significant effect on Correct Response to Letter Stimulus in electrode P8 between 208 and 238 ms, and electrode F8 between 376-378 ms with p-values between .0444 and .034, *df* = 17, *t* = 4.6325; and on Correct Response to Place stimulus in electrode P7 between 318-394 ms with p-values between .0476 and .018, *df* = 14, *t* = 4.3195 (Please see Figure 88 and 89). Other bins were not significant.

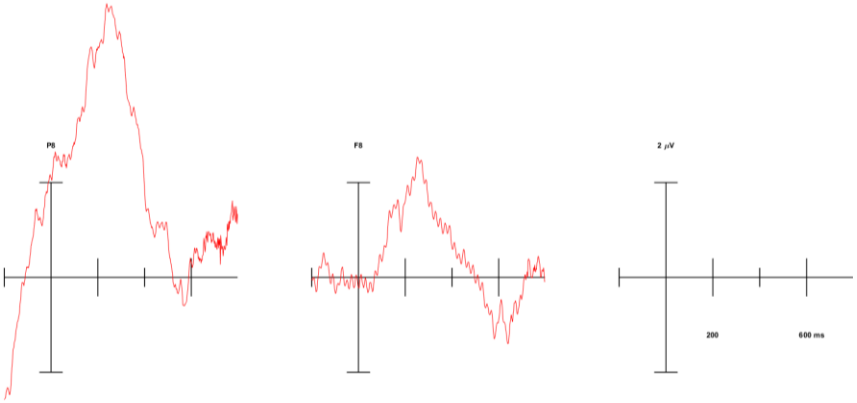


Figure 88: ERP for correct response to letter on P8 and F8 on individual setting 3-back over extraversion, the figure on right shows axis values.

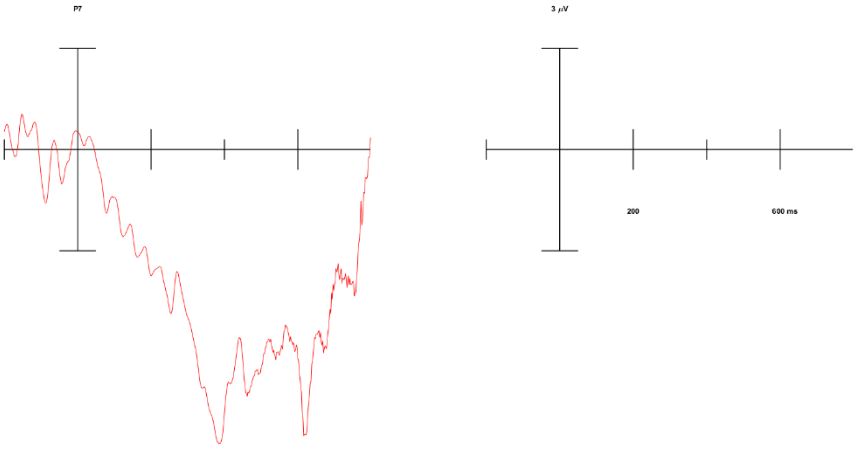


Figure 89: ERP for correct response to place on P7 on individual setting 3-back over extraversion, the figure on right shows axis values.

4.9. EEG Hyperscanning

EEG data from each n-back level in social session was epoched with EEGLAB (Delorme & Makeig, 2004) for -200 to 800 ms of every trial. There were three types of trials: (i) Go trial for the participant sitting on the left side, (ii) Go trial for the participant sitting on the right side, (iii) No-Go trial for both participants. The experiment flow was prepared so that the participants will respond on different trials in order to avoid one of them from blocking the response of the other participant. Therefore, a Go trial for a participant on one side was always a No-Go trial for the participant on the other side.

The epoched data from each n-back level was analyzed with HyPyp (Ayrolles et al., 2021) over each trial type, and also for all trial types combined. The analysis was repeated for five frequency bands: Delta (0.5 - 3.5 Hz), Theta (4 - 7.5 Hz), Alpha (8 - 12 Hz), Beta (12.5 - 29.5 Hz), Gamma (30 - 40 Hz).

The pipeline included individual component analysis and automatic artifact cleaning. Afterwards, Hilbert transform was applied (Burgess, 2013) and it was followed with circular correlation coefficient method (Goldstein et al., 2018) of phase synchrony to calculate interbrain and intrabrain connectivity metrics. For interbrain connectivity analysis, data covering all trial types were used to compare connectivity differences between n-back level blocks. For intrabrain connectivity analysis, the data from (i) and (ii) were separated into own-go and other-go blocks for each n-back level per participant, and then intrabrain connectivity differences were assessed between participants' own go trials and the other participant's trials. Finally, interbrain and intrabrain connectivity figures showing significant comparisons were drawn using HyPyp.

4.9.1. Interbrain Connectivity

Interbrain connectivity results in EEG were analyzed with a repeated measures ANOVA on average connectivity measure per participant in all trials of each n-back level (0-, 1-, 2-, 3-back) for every electrode pair (17 x 17 electrodes: C3, C4, Cz, F3, F4, F7, F8, Fz, O1, O2, P3, P4, P7, P8, Pz, T7, T8) across each frequency band (Alpha, Beta, Delta, Gamma, Theta). Simple Contrast was applied with 0-back as reference. Sidak correction was used on multiple comparisons. In the following tables, the significant results (FDR corrected $p < 0.05$) will be provided for each band, with the electrode of the participant on the left reported first. Please see Figures 90 to 104 for topography plots.

In the alpha band, electrode pairs with significant results are presented in Table 9.

Table 9: Significant results in interbrain connectivity in the alpha band.

Electrode	**Descriptives**	**Statistics**
C3-C3	1-back (M = .32, SE = .22) and 2-back (M = .24, SE = .16) vs. 0-back (M = -.4, SE = .17)	$F(3, 63) = 3.166$, $\eta_p^2 = .131$
C3-O2	1-back (M = .28, SE = .16) and 2-back (M = .43, SE = .19) vs. 0-back (M = -.39, SE = .19)	$F(3, 63) = 4.445$, $\eta_p^2 = .175$
Cz-C3	1-back (M = .76, SE = .2), and 2-back (M = .19, SE = .24) vs. 0-back (M = -.45, SE = .19)	$F(3, 63) = 6.76$, $\eta_p^2 = .244$
O1-O1	3-back (M = -.33, SE = .15) vs. 0-back (M = .29, SE = .17)	$F(1, 21) = 8.019$, $\eta_p^2 = .276$
O2-O2	3-back (M = -.27, SE = .21) vs. 0-back (M = .42, SE = .24)	$F(3, 63) = 5.844$, $\eta_p^2 = .218$
O2-P8	3-back (M = -.31, SE = .18) vs. 0-back (M = .39, SE = .21)	$F(3, 63) = 2.895$, $\eta_p^2 = .121$
P4-P8	2-back (M = -.19, SE = .2) and 3-back (M = -.2, SE = .17) vs. 0-back (M = .53, SE = .2)	$F(3, 63) = 3.233$, $\eta_p^2 = .133$
Pz-O2	2-back (M = .58, SE = .22) vs. 0-back (M = -.23, SE = .25)	$F(3, 63) = 3.189$, $\eta_p^2 = .132$
T7-P8	1-back (M = -.25, SE = .19) vs. 0-back (M = .5, SE = .17)	$F(3, 63) = 2.841$, $\eta_p^2 = .119$

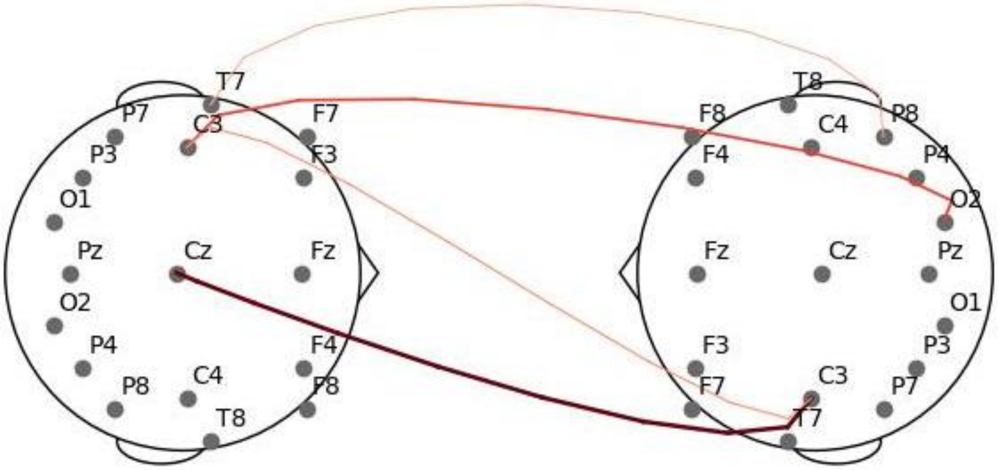


Figure 90: Topography figure showing significant interbrain connectivity comparisons in the alpha band between 1-back and 0-back, the thickness of the line correlates with the η_p^2 value.

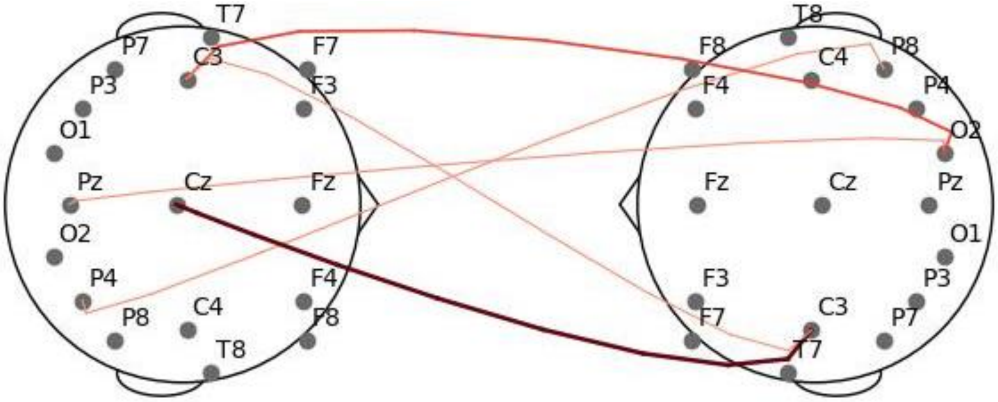


Figure 91: Topography figure showing significant interbrain connectivity comparisons in the alpha band between 2-back and 0-back, the thickness of the line correlates with the η_p^2 value.

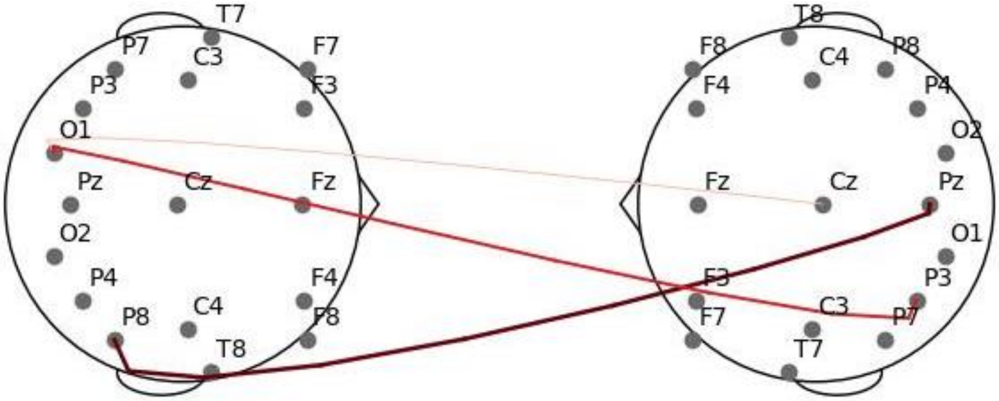


Figure 92: Topography figure showing significant interbrain connectivity comparisons in the alpha band between 3-back and 0-back, the thickness of the line correlates with the η_p^2 value.

In the beta band, electrode pairs with significant results are presented in Table 10.

Table 10: Significant results in interbrain connectivity in the beta band.

Electrode	**Descriptives**	**Statistics**
C3-O1	3-back (M = -.56, SE = .19) vs. 0-back (M = .27, SE = .21)	F(3, 63) = 3.97, η_p^2 = .159
C4-O1	3-back (M = -.6, SE = .23) vs. 0-back (M = .27, SE = .19)	F(3, 63) = 4.316, η_p^2 = .17
Cz-O1	3-back (M = -.83, SE = .21) vs. 0-back (M = .01, SE = .22)	F(3, 63) = 4.837, η_p^2 = .187
Cz-P7	3-back (M = -.78, SE = .25) vs. 0-back (M = .01, SE = .16)	F(3, 63) = 6.041, η_p^2 = .223
Cz-T7	1-back (M = .31, SE = .22) vs. 0-back (M = -.45, SE = .21)	F(3, 63) = 2.788, η_p^2 = .117
F7-P8	3-back (M = .67, SE = .2) vs. 0-back (M = -.28, SE = .18)	F(3, 63) = 5.233, η_p^2 = .199
Fz-Cz	3-back (M = .25, SE = .22) vs. 0-back (M = -.74, SE = .22)	F(3, 63) = 3.858, η_p^2 = .155
Fz-T8	3-back (M = .62, SE = .22) vs. 0-back (M = -.29, SE = .22)	F(3, 63) = 3.11, η_p^2 = .129
O2-P8	3-back (M = .4, SE = .18) vs. 0-back (M = -.56, SE = .24).	F(3, 63) = 3.518, η_p^2 = .143
P8-O1	3-back (M = -.55, SE = .17) vs. 0-back (M = .23, SE = .23)	F(3, 63) = 3.404, η_p^2 = .139
P8-P3	1-back (M = -.3, SE = .18), and 2-back (M = -.26, SE = .17) vs. 0-back (M = .55, SE = 1.22)	F(3, 63) = 4.799, η_p^2 = .186
T8-P3	1-back (M = -.42, SE = .15) vs. 0-back (M = .4, SE = .19)	F(3, 63) = 5.441, η_p^2 = .206

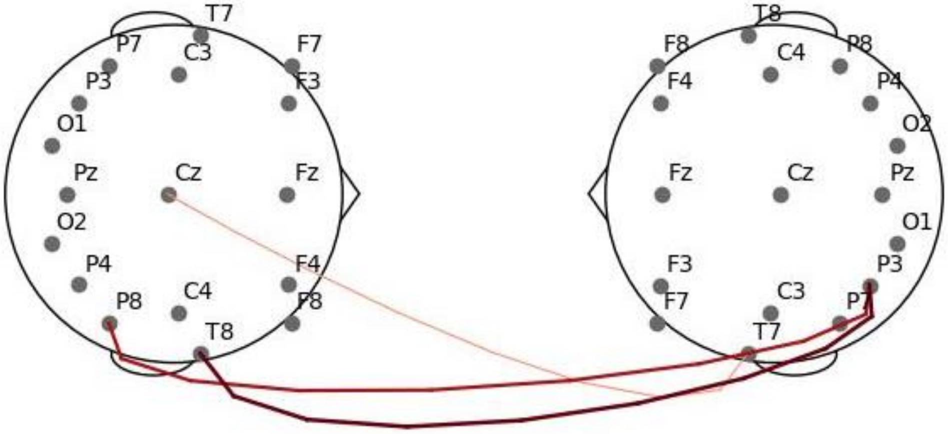


Figure 93: Topography figure showing significant interbrain connectivity comparisons in the beta band between 1-back and 0-back, the thickness of the line correlates with the η_p^2 value.

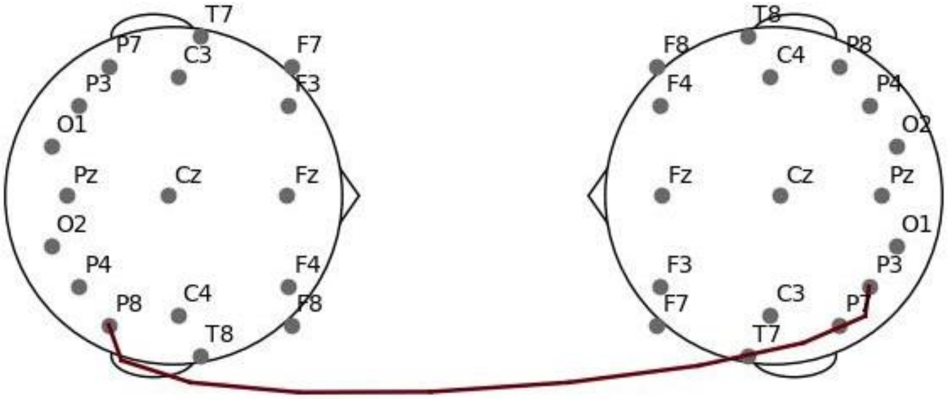


Figure 94: Topography figure showing significant interbrain connectivity comparisons in the beta band between 2-back and 0-back, the thickness of the line correlates with the η_p^2 value.

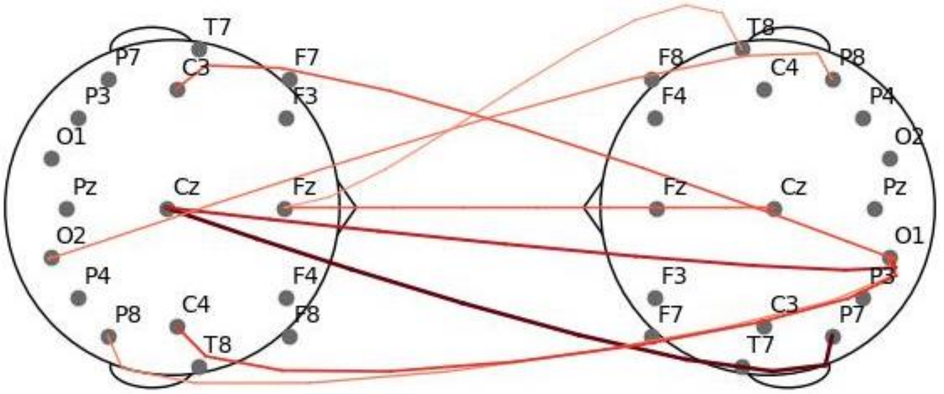


Figure 95: Topography figure showing significant interbrain connectivity comparisons in the beta band between 3-back and 0-back, the thickness of the line correlates with the η_p^2 value.

In the delta band, electrode pairs with significant results are presented in Table 11.

Table 11: Significant results in interbrain connectivity in the delta band.

Elec-trode	**Descriptives**	**Statistics**
C4-Cz	1-back (M = -.45, SE = .2), and 2-back (M = .42, SE = 0.22) vs. 0-back (M = .45, SE = .24)	$F(3, 63) = 3.412$, $\eta_p^2 = .14$
Cz-P7	2-back (M = .44, SE = .2) vs. 0-back (M = -.24, SE = .15)	$F(3, 63) = 2.845$, $\eta_p^2 = .119$
Cz-T7	1-back (M = .4, SE = .19), and 2-back (M = .29, SE = 0.24) vs. 0-back (M = -.48, SE = .2)	$F(3, 63) = 3.62$, $\eta_p^2 = .147$
F4-F3	1-back (M = .48, SE = .19) vs. 0-back (M = -.45, SE = 0.26)	$F(3, 63) = 2.883$, $\eta_p^2 = .121$
F4-F7	1-back (M = .14, SE = .21), 2-back (M = .23, SE = .21), and 3-back (M = .09, SE = .2) vs. 0-back (M = -.53, SE = .16)	$F(3, 63) = 2.947$, $\eta_p^2 = .123$
F8-F7	2-back (M = .41, SE = .17), and 3-back (M = .38, SE = .21) vs. 0-back (M = -.41, SE = .2)	$F(3, 63) = 3.786$, $\eta_p^2 = .153$
F8-T7	2-back (M = .57, SE = .2) vs. 0-back (M = -.23, SE = .16)	$F(3, 63) = 2.885$, $\eta_p^2 = .121$
Fz-T7	1-back (M = .57, SE = 0.23) vs. 0-back (M = -.46, SE = 0.23)	$F(3, 63) = 3.445$, $\eta_p^2 = .141$
O1-F7	1-back (M = .63, SE = 0.24) vs. 0-back (M = .03, SE = .21)	$F(3, 63) = 3.404$, $\eta_p^2 = .139$
O1-T7	1-back (M = .53, SE = .19) vs. 0-back (M = -.1, SE = 0.22)	$F(3, 63) = 4.193$, $\eta_p^2 = .166$
P4-F7	1-back (M = .44, SE = .17) vs. 0-back (M = -.22, SE = .15)	$F(3, 63) = 2.766$, $\eta_p^2 = .116$
P4-T7	1-back (M = .43, SE = .14) vs. 0-back (M = -.26, SE = .15)	$F(3, 63) = 3.674$, $\eta_p^2 = .149$
P7-O1	2-back (M = .64, SE = .19) vs. 0-back (M = .04, SE = .19)	$F(3, 63) = 3.515$, $\eta_p^2 = .143$
P8-Cz	2-back (M = -.39, SE = .23) vs. 0-back (M = .53, SE = .24)	$F(3, 63) = 2.917$, $\eta_p^2 = .122$
T8-Cz	2-back (M = -.51, SE = .27) vs. 0-back (M = .4, SE = .27)	$F(3, 63) = 2.791$, $\eta_p^2 = .117$
T8-P3	2-back (M = -.51, SE = .29) vs. 0-back (M = .53, SE = .2)	$F(3, 63) = 3.566$, $\eta_p^2 = .145$
C4-F7	3-back (M = .42, SE = .17) vs. 0-back (M = -.19, SE = .22)	$F(3, 63) = 6.699$, $\eta_p^2 = .242$
F8-P8	3-back (M = .51, SE = .22) vs. 0-back (M = -.24, SE = .19)	$F(3, 63) = 6.229$, $\eta_p^2 = .229$
Cz-F7	3-back (M = .17, SE = .13) vs. 0-back (M = -.45, SE = .18)	$F(3, 63) = 5.77$, $\eta_p^2 = .216$
O1-T8	3-back (M = -.26, SE = .2) vs. 0-back (M = . 38, SE = .19)	$F(3, 63) = 5.61$, $\eta_p^2 = .211$
Fz-F7	3-back (M = .26, SE = .23) vs. 0-back (M = -.39, SE = .2)	$F(3, 63) = 5.198$, $\eta_p^2 = .198$
C4-P8	3-back (M = .29, SE = .19) vs. 0-back (M = -.31, SE = .2)	$F(3, 63) = 5.164$, $\eta_p^2 = .197$

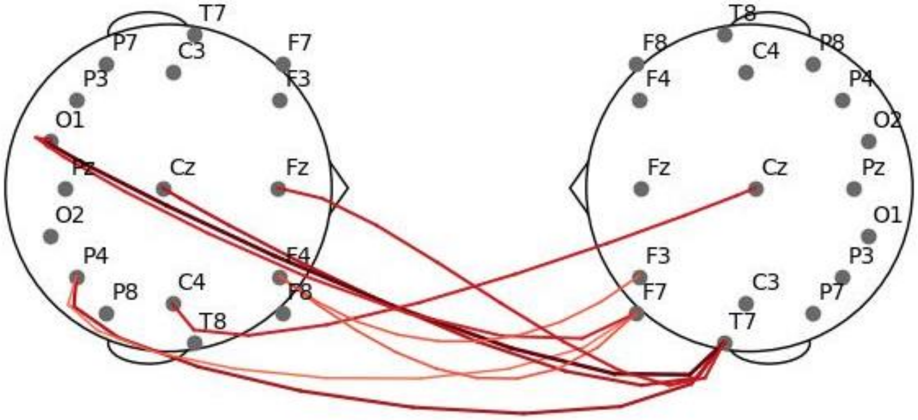


Figure 96: Topography figure showing significant interbrain connectivity comparisons in the delta band between 1-back and 0-back, the thickness of the line correlates with the η_p^2 value.

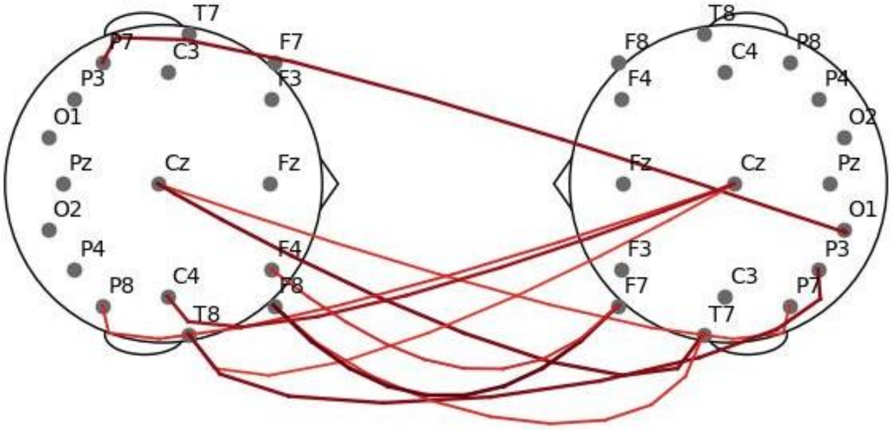


Figure 97: Topography figure showing significant interbrain connectivity comparisons in the delta band between 2-back and 0-back, the thickness of the line correlates with the η_p^2 value.

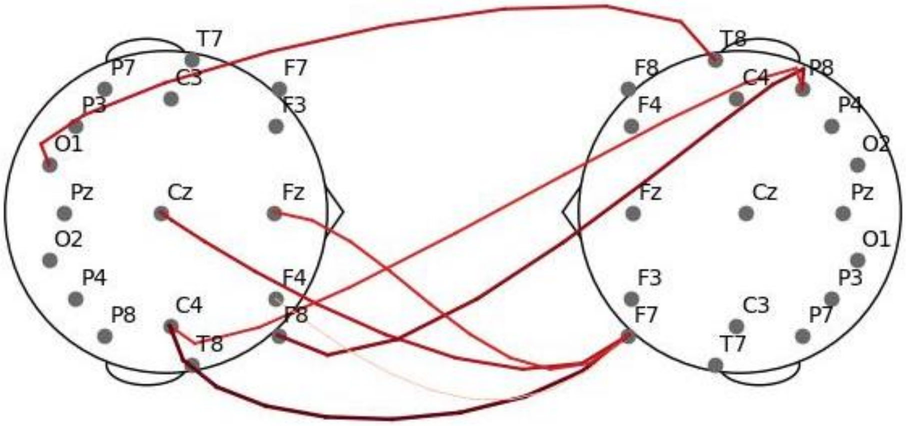


Figure 98: Topography figure showing significant interbrain connectivity comparisons in the delta band between 3-back and 0-back, the thickness of the line correlates with the η_p^2 value.

In the gamma band, electrode pairs with significant results are presented in Table 12.

Table 12: Significant results in interbrain connectivity in the gamma band.

Electrode	**Descriptives**	**Statistics**
C3-P3	3-back ($M = -.4$, $SE = .2$) vs. 0-back ($M = .14$, $SE = .2$)	$F(3, 63) = 2.798$, $\eta_p^2 = .118$
C3-Pz	3-back ($M = -.54$, $SE = .3$) vs. 0-back ($M = .43$, $SE = .2$)	$F(3, 63) = 3.803$, $\eta_p^2 = .153$
C4-Cz	1-back ($M = -.39$, $SE = .23$), and 2-back ($M = -.18$, $SE = .23$) vs. 0-back ($M = .59$, $SE = .19$)	$F(3, 63) = 4.612$, $\eta_p^2 = .18$
C4-O1	3-back ($M = .3$, $SE = .18$) vs. 0-back ($M = -.46$, $SE = .25$)	$F(3, 63) = 2.875$, $\eta_p^2 = .12$
F3-O1	2-back ($M = .34$, $SE = .18$) vs. 0-back ($M = -.24$, $SE = .22$)	$F(3, 63) = 3.587$, $\eta_p^2 = .146$
F4-O1	1-back ($M = .63$, $SE = .21$) vs. 0-back ($M = -.12$, $SE = .2$)	$F(3, 63) = 4.349$, $\eta_p^2 = .172$
F7-O1	1-back ($M = .33$, $SE = .24$), and 3-back ($M = .01$, $SE = .21$) vs. 0-back ($M = -.58$, $SE = .17$)	$F(3, 63) = 3.184$, $\eta_p^2 = .132$
F8-O1	3-back ($M = .48$, $SE = .23$) vs. 0-back ($M = -.36$, $SE = .25$)	$F(3, 63) = 2.873$, $\eta_p^2 = .12$
O2-Cz	1-back ($M = -.43$, $SE = .21$) vs. 0-back ($M = .47$, $SE = .23$)	$F(3, 63) = 3.285$, $\eta_p^2 = .135$
O2-Fz	3-back ($M = -.49$, $SE = .18$) vs. 0-back ($M = .29$, $SE = .23$)	$F(3, 63) = 2.881$, $\eta_p^2 = .121$
P7-Fz	3-back ($M = -.48$, $SE = .2$) vs. 0-back ($M = .15$, $SE = .2$)	$F(3, 63) = 3.916$, $\eta_p^2 = .157$
P8-Cz	1-back ($M = -.48$, $SE = .21$) vs. 0-back ($M = .5$, $SE = .21$)	$F(3, 63) = 3.785$, $\eta_p^2 = .153$
P8-F7	1-back ($M = .29$, $SE = .19$), and 3-back ($M = .12$, $SE = .2$) vs. 0-back ($M = -.59$, $SE = .17$)	$F(3, 63) = 3.291$, $\eta_p^2 = .135$
T7-F3	3-back ($M = -.29$, $SE = .16$) vs. 0-back ($M = .42$, $SE = .17$)	$F(3, 63) = 3.041$, $\eta_p^2 = .126$
T8-Cz	1-back ($M = -.65$, $SE = .2$) vs. 0-back ($M = .22$, $SE = .24$)	$F(3, 63) = 2.858$, $\eta_p^2 = .12$

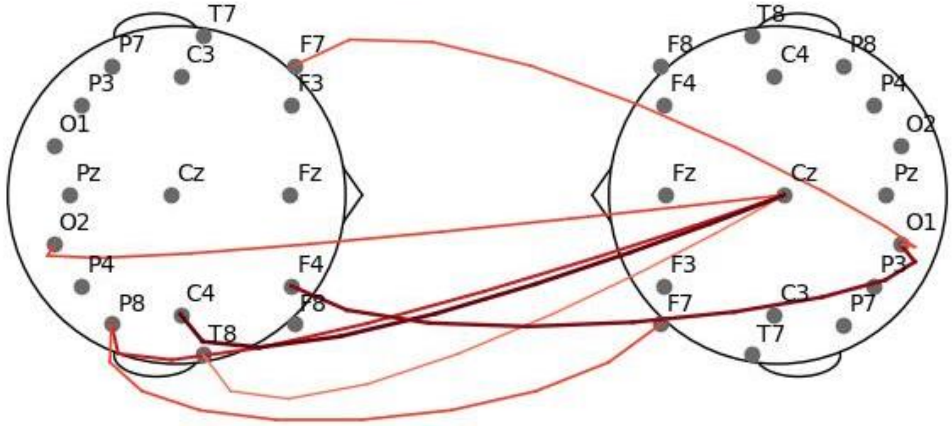


Figure 99: Topography figure showing significant interbrain connectivity comparisons in the gamma band between 1-back and 0-back, the thickness of the line correlates with the $\eta_p{}^2$ value.

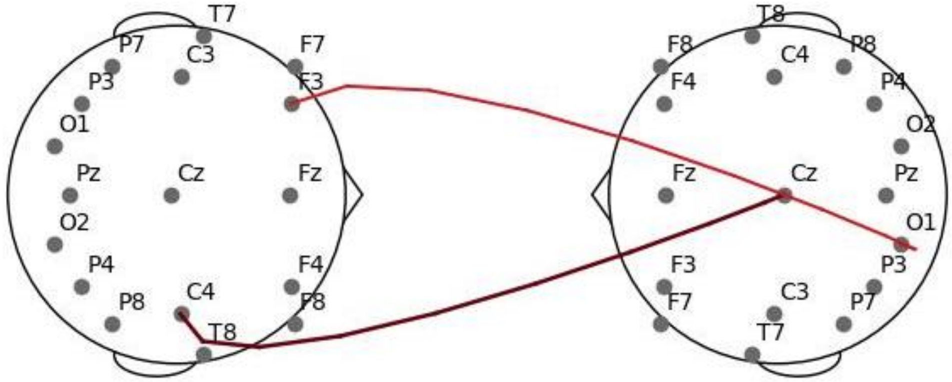


Figure 100: Topography figure showing significant interbrain connectivity comparisons in the gamma band between 2-back and 0-back, the thickness of the line correlates with the $\eta_p{}^2$ value.

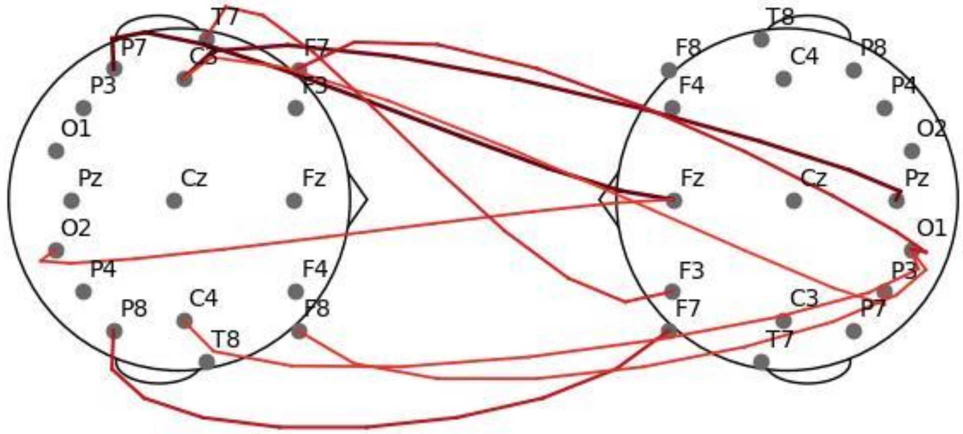


Figure 101: Topography figure showing significant interbrain connectivity comparisons in the gamma band between 3-back and 0-back, the thickness of the line correlates with the $\eta_p{}^2$ value.

In the theta band, electrode pairs with significant results are presented in Table 13.

Table 13: Significant results in interbrain connectivity in the theta band.

Electrode	**Descriptives**	**Statistics**
F3-P3	1-back (*M* = .51, *SE* = .22), and 3-back (*M* = .33, *SE* = .21) vs. 0-back (*M* = -.6, *SE* = .26)	$F(3, 63) = 4.045$, $\eta_p^2 = .162$
F4-P8	2-back (*M* = .53, *SE* = .19) vs. 0-back (*M* = -.19, *SE* = .19)	$F(3, 63) = 3.044$, $\eta_p^2 = .127$
F7-Pz	3-back (*M* = -.42, *SE* = .22) vs. 0-back (*M* = .21, *SE* = .19)	$F(3, 63) = 3.007$, $\eta_p^2 = .125$
F8-F3	1-back (*M* = -.2, *SE* = .19), 2-back (*M* = -.25, *SE* = .18), and 3-back (*M* = -.07, *SE* = .19) vs. 0-back (*M* = .48, *SE* = .18)	$F(3, 63) = 3.649$, $\eta_p^2 = .148$
Fz-Fz	1-back (*M* = .31, *SE* = .19) vs. 0-back (*M* = -.37, *SE* = .17)	$F(3, 63) = 2.913$, $\eta_p^2 = .122$
Fz-P4	1-back (*M* = .54, *SE* = .18) vs. 0-back (*M* = -.32, *SE* = .19)	$F(3, 63) = 3.381$, $\eta_p^2 = .139$
Fz-P7	1-back (*M* = .52, *SE* = .19) vs. 0-back (*M* = -.3, *SE* = .14)	$F(3, 63) = 3.157$, $\eta_p^2 = .131$
O2-F4	1-back (*M* = -.66, *SE* = .18) vs. 0-back (*M* = .17, *SE* = .24)	$F(3, 63) = 3.918$, $\eta_p^2 = .157$
O2-O1	1-back (*M* = -.62, *SE* = .19) vs. 0-back (*M* = .06, *SE* = .22)	$F(3, 63) = 3.433$, $\eta_p^2 = .141$
P3-P3	1-back (*M* = .34, *SE* = .2), and 2-back (*M* = .39, *SE* = .18) vs. 0-back (*M* = -.45, *SE* = .28)	$F(3, 63) = 2.847$, $\eta_p^2 = .119$
P3-P7	1-back (*M* = .21, *SE* = .15), and 3-back (*M* = .24, *SE* = .21) vs. 0-back (*M* = -.49, *SE* = .23)	$F(3, 63) = 3.476$, $\eta_p^2 = .142$
P7-O1	3-back (*M* = .43, *SE* = .25) vs. 0-back (*M* = -.3, *SE* = .24)	$F(3, 63) = 4.692$, $\eta_p^2 = .183$
T8-O1	1-back (*M* = -.42, *SE* = .19), and 2-back (*M* = -.3, *SE* = .21) vs. 0-back (*M* = .62, *SE* = .21)	$F(3, 63) = 4.92$, $\eta_p^2 = .19$
T8-P8	1-back (*M* = -.46, *SE* = .24) vs. 0-back (*M* = .19, *SE* = .15)	$F(3, 63) = 2.911$, $\eta_p^2 = .122$

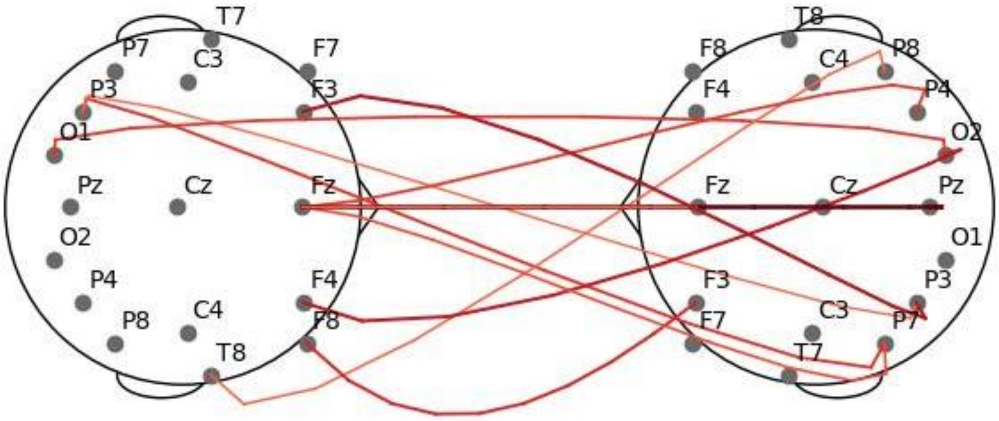


Figure 102: Topography figure showing significant interbrain connectivity comparisons in the theta band between 1-back and 0-back, the thickness of the line correlates with the η_p^2 value.

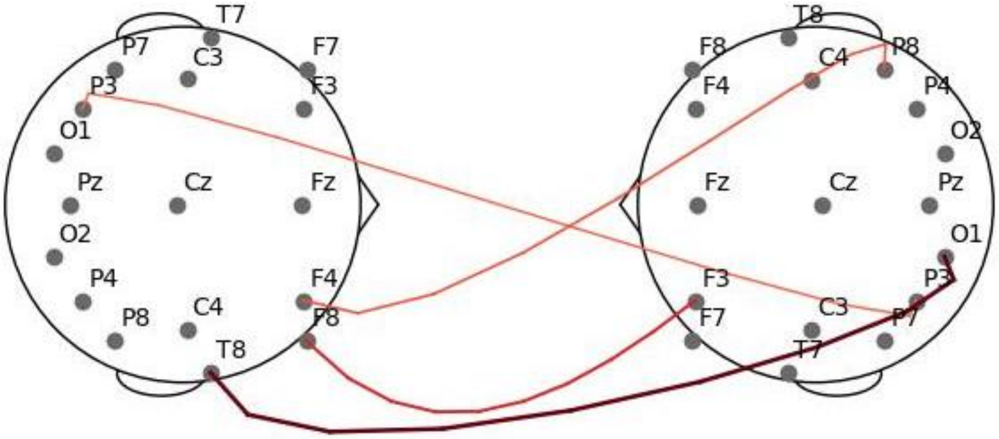


Figure 103: Topography figure showing significant interbrain connectivity comparisons in the theta band between 2-back and 0-back, the thickness of the line correlates with the η_p^2 value.

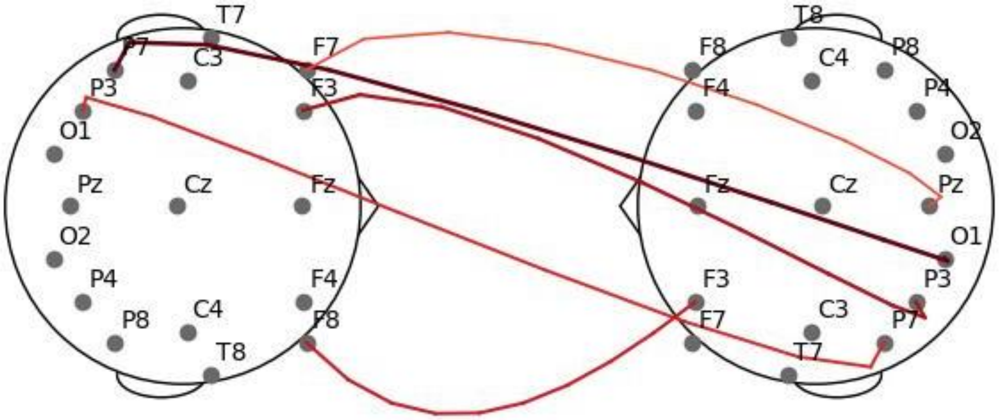


Figure 104: Topography figure showing significant interbrain connectivity comparisons in the theta band between 3-back and 0-back, the thickness of the line correlates with the η_p^2 value.

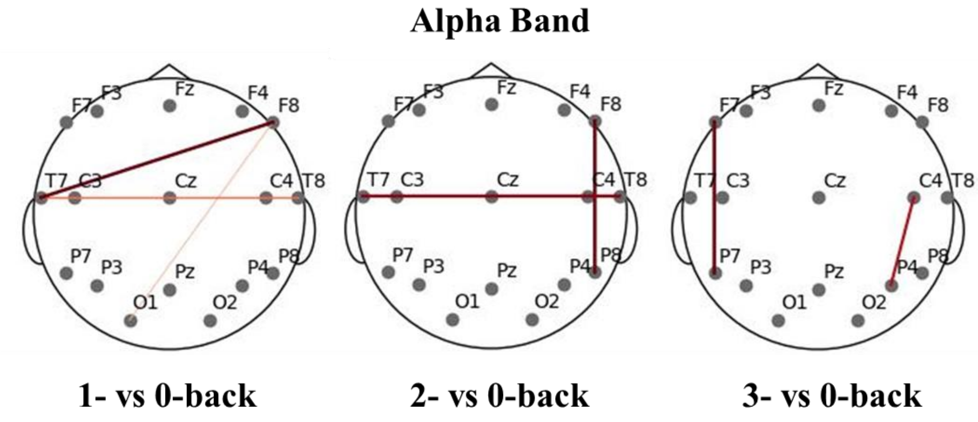
4.9.2. Intrabrain Connectivity Comparison of Own and Other's Go Trials

Intrabrain connectivity results in EEG were analyzed with a 2x4 repeated measures ANOVA on average connectivity measure per participant in their own go trials and the other participant's go trials of each n-back level (0-, 1-, 2-, 3-back) for every electrode pair (17 x 17 electrodes: C3, C4, Cz, F3, F4, F7, F8, Fz, O1, O2, P3, P4, P7, P8, Pz, T7, T8) across each frequency band (Alpha, Beta, Delta, Gamma, Theta). Simple Contrast was applied with 0-back as reference. Sidak correction was used on multiple comparisons. FDR corrected results with $p < 0.05$ are provided in Tables 14 to 18, with topography figures showing the η_p^2 values of significant comparisons in Figures 105 to 109.

In the alpha band, electrode pairs with significant results are presented in Table 14.

Table 14: Significant results in intrabrain analysis of own and other's go trials in the alpha band.

Elec-trode	**Descriptives**	**Statistics**
C4-P4	3-back (*M* = .59, *SE* = 1.12 in own-go trials, *M* = .6, *SE* = .95 in other-go trials) vs. 0-back (*M* = .25, *SE* = .93 in own-go trials, *M* = .19, *SE* = .93 in other-go trials)	*F*(3, 129) = 3.176, η_p^2 = .069
C4-P7	3-back (*M* = .26, *SE* = .15 in own-go trials, *M* = .51, *SE* = .17 in other-go trials) vs. 0-back (*M* = .05, *SE* = .16 in own-go trials, *M* = .09, *SE* = .14 in other-go trials)	*F*(3, 129) = 3.652, η_p^2 = .078
F8-O1	1-back (*M* = .15, *SE* = .13 in own, *M* = .19, *SE* = .13 in other) vs. 0-back (*M* = -.13, *SE* = .13 in own, *M* = -.13, *SE* = .14 in other)	*F*(3, 129) = 2.816, η_p^2 = .061
F8-P8	2-back (*M* = .48, *SE* = .14 in own, *M* = .08, *SE* = .15 in other) vs. 0-back (*M* = -.08, *SE* = .13 in own, *M* = .41, *SE* = .14 in other)	*F*(3, 129) = 4.165, η_p^2 = .088
F8-T7	1-back (*M* = -.07, *SE* = .14 in own, *M* = .18, *SE* = .14 in other) vs. 0-back (*M* = .37, *SE* = .16 in own, *M* = .03, *SE* = .13 in other)	*F*(3, 129) = 6.749, η_p^2 = .136
T7-T8	1-back (*M* = -.19, *SE* = .14 in own, *M* = -.04, *SE* = .14 in other) and 2-back (*M* = -.35, *SE* = .12 in own, *M* = -.08, *SE* = .13 in other) vs. 0-back (*M* = .26, *SE* = .15 in own, *M* = .15, *SE* = .14 in other)	*F*(3, 129) = 3.966, η_p^2 = .084



Alpha Band

1- vs 0-back

2- vs 0-back

3- vs 0-back

Figure 105: Topography figure showing significant intrabrain connectivity comparisons in the alpha band n-back levels and interaction of n-back levels with task setting, line thickness correlates with the η_p^2 value.

In the beta band, electrode pairs with significant results are presented in Table 15.

Table 15: Significant results in intrabrain analysis of own and other's go trials in the beta band.

Elec-trode	**Descriptives**	**Statistics**
C3-Cz	2-back (*M* = -.01, *SE* = .13 in own-go, *M* = .55, *SE* = .13 in other) vs. 0-back (*M* = .3, *SE* = .16 in own-go, *M* = .23, *SE* = .16 in other)	*F*(3, 129) = 2.868, η_p^2 = .063
C3-T8	2-back (*M* = .22, *SE* = .12 in own-go, *M* = .02, *SE* = .12 in other) vs. 0-back (*M* = -.3, *SE* = .11 in own-go, *M* = -.06, *SE* = .13 in other)	*F*(3, 129) = 3.143, η_p^2 = .068
C3-C4	2-back (*M* = .27, *SE* = .16 in own-go, *M* = .26, *SE* = .15 in other) and 3-back (*M* = .21, *SE* = .12 in own-go, *M* = .21, *SE* = .14 in other) vs. 0-back (*M* = -.07, *SE* = .13 in own-go, *M* = -.05, *SE* = .12 in other)	*F*(3, 129) = 4.092, η_p^2 = .087
Cz-F3	3-back (*M* = .27, *SE* = .18 in own-go, *M* = -.19, *SE* = .15 in other) vs. 0-back (*M* = .08, *SE* = .16 in own-go, *M* = .15, *SE* = .15 in other)	*F*(3, 129) = 4.503, η_p^2 = .095
F3-Pz	1-back (*M* = -.27, *SE* =.12 in own-go, *M* = -.29, *SE* = .13 in other) vs. 0-back (*M* = -.12, *SE* = .13 in own-go, *M* = .13, *SE* = .15 in other)	*F*(3, 129) = 2.77, η_p^2 = .061
F3-T8	2-back (*M* = .09, *SE* =.13 in own-go, *M* = -.18, *SE* = .12 in other) vs. 0-back (*M* = -.36, *SE* = .12 in own-go, *M* = -.05, *SE* = .14 in other)	*F*(3, 129) = 2.839, η_p^2 = .062
F7-P4	3-back (*M* = -.01, *SE* = .13 in own-go, *M* = -.37, *SE* = .11 in other) vs. 0-back (*M* = -.22, *SE* = .14 in own-go, *M* = .02, *SE* = .11 in other)	*F*(3, 129) = 4.428, η_p^2 = .093
F7-Pz	1-back (*M* = -.32, *SE* =.11 in own-go, *M* = -.01, *SE* = .15 in other) and 2-back (*M* = -.26, *SE* =.12 in own-go, *M* = .07, *SE* = .12 in other) vs. 0-back (*M* = .08, *SE* = .15 in own-go, *M* = .15, *SE* = .14 in other)	*F*(3, 129) = 2.704, η_p^2 = .059
F8-P7	2-back (*M* = .22, *SE* = .12 in own-go, *M* = -.15, *SE* = .13 in other) vs. 0-back (*M* = -.09, *SE* = .1 in own-go, *M* = -.03, *SE* = .13 in other)	*F*(3, 129) = 3.291, η_p^2 = .071
P7-T7	2-back (*M* = .55, *SE* = .18 in own-go, *M* = .48, *SE* = .15 in other) vs. 0-back (*M* = .18, *SE* = .14 in own-go, *M* = .18, *SE* = .14 in other)	*F*(3, 129) = 4.532, η_p^2 = .095
P7-T8	2-back (*M* = .41, *SE* = .14 in own-go, *M* = -.11, *SE* = .12 in other) vs. 0-back (*M* = -.15, *SE* = .12 in own-go, *M* = -.03, *SE* = .14 in other)	*F*(3, 129) = 6.039, η_p^2 = .123

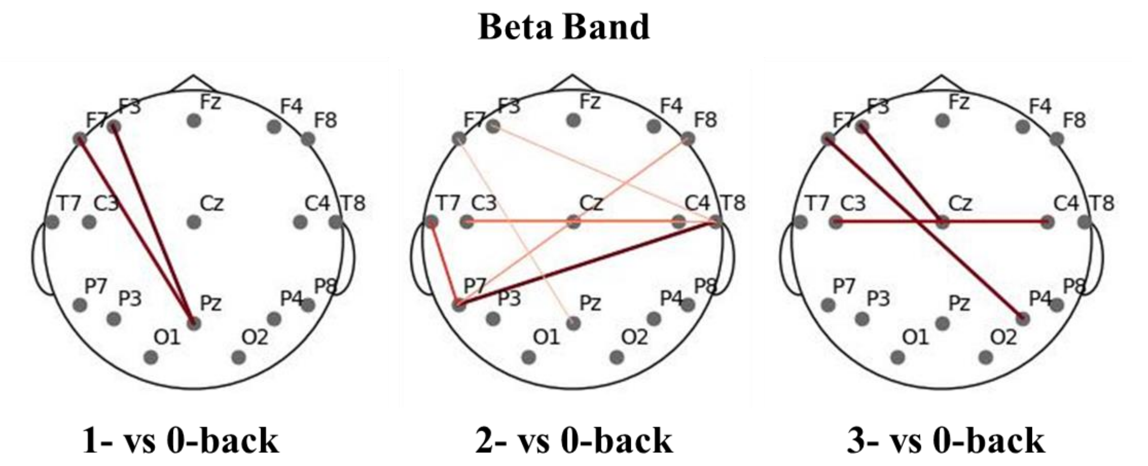
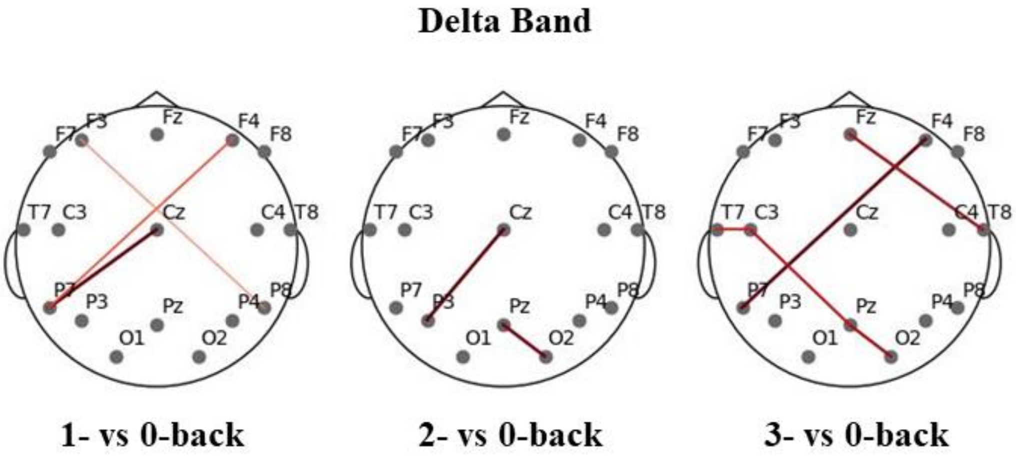


Figure 106: Topography figure showing significant intrabrain connectivity comparisons in the beta band n-back levels and interaction of n-back levels with task setting, line thickness correlates with the η_p^2 value.

In the delta band, electrode pairs with significant results are presented in Table 16. The only electrode pair which showed an effect on trial type was in delta band C4 and P3 (F(1, 43) = 5.056, $p < .05$, $\eta_p^2 = .105$), as connectivity measures in own-go trials ($M = -.03$, $SE = .06$) were significantly different than other-go trials ($M = -.28$, $SE = .07$).

Table 16: Significant results in intrabrain analysis of own and other's go trials in the delta band.

Electrode	Descriptives	Statistics
C3-Pz	3-back ($M = .22$, $SE = .13$ in own-go, $M = .04$, $SE = .12$ in other-go) vs. 0-back ($M = -.12$, $SE = .13$ in own-go, $M = -.32$, $SE = .11$ in other-go)	$F(3, 129) = 2.937$, $\eta_p^2 = .064$
C3-T7	3-back ($M = .42$, $SE = .14$ in own-go, $M = .06$, $SE = .13$ in other-go) vs. 0-back ($M = -.05$, $SE = .12$ in own-go, $M = .17$, $SE = .14$ in other-go)	$F(3, 129) = 2.737$, $\eta_p^2 = .06$
Cz-P3	2-back ($M = .25$, $SE = .14$ in own-go, $M = .13$, $SE = .15$ in other-go) vs. 0-back ($M = -.13$, $SE = .15$ in own-go, $M = -.25$, $SE = .15$ in other-go)	$F(3, 129) = 3.233$, $\eta_p^2 = .07$
Cz-P7	1-back ($M = .12$, $SE = .11$ in own-go, $M = -.02$, $SE = .13$ in other-go) vs. 0-back ($M = -.26$, $SE = .13$ in own-go, $M = -.23$, $SE = .13$ in other-go	$F(3, 129) = 5.168$, $\eta_p^2 = .107$
F3-P8	1-back ($M = .01$, $SE = .14$ in own-go, $M = -.31$, $SE = .12$ in other-go) vs. 0-back ($M = -.27$, $SE = .12$ in own-go, $M = .05$, $SE = .12$ in other-go)	$F(3, 129) = 2.851$, $\eta_p^2 = .062$
F4-P7	1-back ($M = -.07$, $SE = .13$ in own-go, $M = .11$, $SE = .15$ in other-go) and 3-back ($M = -.35$, $SE = .12$ in own-go, $M = -.01$, $SE = .13$ in other-go) vs. 0-back ($M = .13$, $SE = .1$ in own-go, $M = -.29$, $SE = .14$ in other-go)	$F(3, 129) = 3.496$, $\eta_p^2 = .075$
Fz-T8	3-back ($M = -.35$, $SE = .12$ in own-go, $M = .12$, $SE = .13$ in other-go) vs. 0-back ($M = .18$, $SE = .14$ in own-go, $M = -.14$, $SE = .13$ in other-go)	$F(3, 129) = 3.608$, $\eta_p^2 = .077$
O2-Pz	2-back ($M = .2$, $SE = .16$ in own-go, $M = .17$, $SE = .12$ in other-go) and 3-back ($M = .01$, $SE = .14$ in own-go, $M = .36$, $SE = .13$ in other-go) vs. 0-back ($M = -.16$, $SE = .14$ in own-go, $M = -.11$, $SE = .15$ in other-go)	$F(3, 129) = 3.122$, $\eta_p^2 = .068$


Delta Band

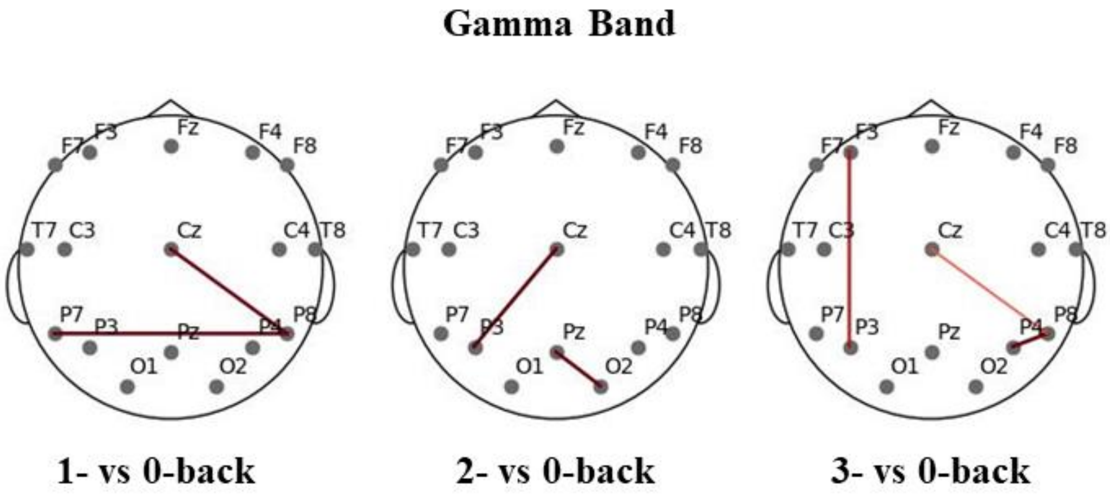
1- vs 0-back **2- vs 0-back** **3- vs 0-back**

Figure 107: Topography figure showing significant intrabrain connectivity comparisons in the delta band n-back levels and interaction of n-back levels with task setting, line thickness correlates with the η_p^2 value.

In the gamma band, electrode pairs with significant results are presented in Table 17.

Table 17: Significant results in intrabrain analysis of own and other's go trials in the gamma band.

Elec-trode	**Descriptives**	**Statistics**
Cz-P3	2-back (M = .09, SE = .16 in own-go, M = .26, SE = .14 in other-go) vs. 0-back (M = -.23, SE = .14 in own-go, M = -.29, SE = .13 in other-go)	$F(3, 129) = 3.625$, $\eta_p^2 = .078$
Cz-P8	1-back (M = -.24, SE = .13 in own-go, M = -.37, SE = .12 in other-go), 3-back (M = -.15, SE = .11 in own-go, M = .02, SE = .16 in other-go) vs. 0-back (M = -.3, SE = .11 in own-go, M = -.51, SE = .11 in other-go)	$F(3, 129) = 2.701$, $\eta_p^2 = .059$
F3-P3	3-back (M = -.09, SE = .12 in own-go, M = .33, SE = .15 in other-go) vs. 0-back (M = .07, SE = .13 in own-go, M = -.19, SE = .12 in other-go)	$F(3, 129) = 3.561$, $\eta_p^2 = .076$
O2-Pz	2-back (M = .45, SE = .15 in own-go, M = .26, SE = .14 in other-go) vs. 0-back (M = .08, SE = .14 in own-go, M = .12, SE = .11 in other-go)	$F(3, 129) = 3.584$, $\eta_p^2 = .077$
P4-P8	3-back (M = .59, SE = .16 in own-go, M = .03, SE = .15 in other-go) vs. 0-back (M = .26, SE = .14 in own-go, M = .36, SE = .17 in other-go)	$F(3, 129) = 4.068$, $\eta_p^2 = .086$
P7-P8	1-back (M = -.01, SE = .17 in own-go, M = -.12, SE = .13 in other-go) vs. 0-back (M = .15, SE = .15 in own-go, M = .24, SE = .14 in other-go)	$F(3, 129) = 2.769$, $\eta_p^2 = .06$


Gamma Band

1- vs 0-back

2- vs 0-back

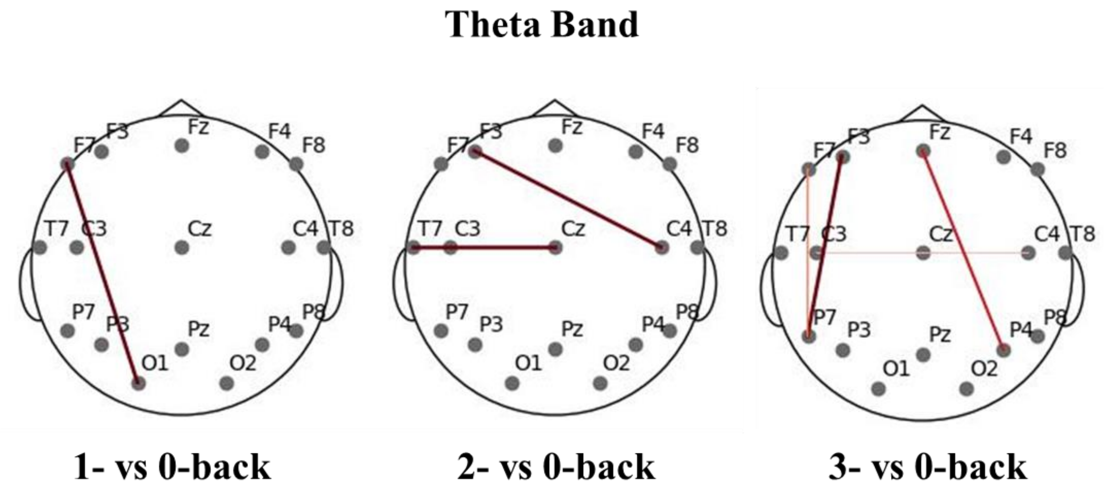
3- vs 0-back

Figure 108: Topography figure showing significant intrabrain connectivity comparisons in the gamma band n-back levels and interaction of n-back levels with task setting, line thickness correlates with the η_p^2 value.

In the theta band, electrode pairs with significant results are presented in Table 18.

Table 18: Significant results in intrabrain analysis of own and other's go trials in the theta band.

Electrode	**Descriptives**	**Statistics**
C3-C4	3-back (*M* = .26, *SE* = .15 in own-go, *M* = .23, *SE* = .16 in other-go) vs. 0-back (*M* = -.12, *SE* = .12 in own-go, *M* = .05, *SE* = .12 in other-go)	*F*(3, 129) = 2.779, η_p^2 = .061
C4-F3	2-back (*M* = .17, *SE* = .14 in own-go, *M* = -.11, *SE* = .14 in other-go) vs. 0-back (*M* = -.15, *SE* = .12 in own-go, *M* = .08, *SE* = .11 in other-go)	*F*(3, 129) = 3.082, η_p^2 = .067
Cz-T7	2-back (*M* = -.15, *SE* = .14 in own-go, *M* = -.08, *SE* = .13 in other-go) vs. 0-back (*M* = .25, *SE* = .14 in own-go, *M* = .11, *SE* = .16 in other-go)	*F*(3, 129) = 3.16, η_p^2 = .068
F3-P7	3-back (*M* = -.49, *SE* = .09 in own-go, *M* = .13, *SE* = .13 in other-go) vs. 0-back (*M* = -.1, *SE* = .14 in own-go, *M* = -.07, *SE* = .12 in other-go)	*F*(3, 129) = 6.56, η_p^2 = .132
F7-O1	1-back (*M* = .06, *SE* = .14 in own-go, *M* = .15, *SE* = .14 in other-go) vs. 0-back (*M* = -.13, *SE* = .13 in own-go, *M* = -.23, *SE* = .13 in other-go)	*F*(3, 129) = 3.03, η_p^2 = .066
F7-P7	3-back (*M* = -.27, *SE* = .11 in own-go, *M* = .25, *SE* = .14 in other-go) vs. 0-back (*M* = -.02, *SE* = .13 in own-go, *M* = -.01, *SE* = .13 in other-go)	*F*(3, 129) = 3.649, η_p^2 = .078
Fz-P4	3-back (*M* = -.43, *SE* = .13 in own-go, *M* = .09, *SE* = .15 in other-go) vs. 0-back (*M* = -.24, *SE* = .13 in own-go, *M* = .25, *SE* = .12 in other-go)	*F*(3, 129) = 5.252, η_p^2 = .109



1- vs 0-back

2- vs 0-back

3- vs 0-back

Figure 109: Topography figure showing significant intrabrain connectivity comparisons in the theta band n-back levels and interaction of n-back levels with task setting, line thickness correlates with the η_p^2 value.

4.9.3. Intrabrain Connectivity Comparison Between Task Settings

All trials in the individual task setting were compared to all trials in the social task setting for each n-back level (0-, 1-, 2-, 3-back) for every electrode pair (17 x 17 electrodes: C3, C4, Cz, F3, F4, F7, F8, Fz, O1, O2, P3, P4, P7, P8, Pz, T7, T8) across each frequency band (Alpha, Beta, Delta, Gamma, Theta) with a 2x4 repeated measures ANOVA on average EEG intrabrain connectivity measure per participant. Simple Contrast was applied with 0-back as reference. Sidak correction was used on multiple comparisons. FDR corrected results with $p < 0.05$ are provided in Tables 19 to 28, with topography figures showing the η_p^2 values of significant comparisons in Figures 110 to 119.

In the alpha band, the electrode pairs which showed an effect on task setting are presented in Table 19.

Table 19: Significant results in intrabrain analysis of individual and social trials in the alpha band.

Electrode	**Descriptives**	**Statistics**
C3-F7	Individual ($M = .04$, $SE = .1$) vs. social ($M = .47$, $SE = .12$)	$F(1, 43) = 11.68$, $\eta_p^2 = .214$
C3-F8	Individual ($M = -.06$, $SE = .08$) vs. social ($M = .29$, $SE = .1$)	$F(1, 43) = 6.929$, $\eta_p^2 = .139$
C3-Fz	Individual ($M = -.1$, $SE = .08$) vs. social ($M = .15$, $SE = .08$)	$F(1, 43) = 5.109$, $\eta_p^2 = .106$
C3-O1	Individual ($M = .14$, $SE = .1$) vs. social ($M = -.21$, $SE = .07$)	$F(1, 43) = 8.546$, $\eta_p^2 = .166$
C4-F8	Individual ($M = .04$, $SE = .11$) vs. social ($M = .42$, $SE = .11$)	$F(1, 43) = 5.954$, $\eta_p^2 = .122$
Cz-O2	Individual ($M = -.02$, $SE = .08$) vs. social ($M = -.25$, $SE = .08$)	$F(1, 43) = 5.048$, $\eta_p^2 = .105$
Cz-P8	Individual ($M = .01$, $SE = .1$) vs. social ($M = -.3$, $SE = .07$)	$F(1, 43) = 8.986$, $\eta_p^2 = .173$
F3-F8	Individual ($M = -.23$, $SE = .08$) vs. social ($M = .11$, $SE = .09$)	$F(1, 43) = 7.042$, $\eta_p^2 = .141$
F3-O2	Individual ($M = .12$, $SE = .1$) vs. social ($M = -.17$, $SE = .08$)	$F(1, 43) = 4.443$, $\eta_p^2 = .094$
F3-P8	Individual ($M = .06$, $SE = .09$) vs. social ($M = -.21$, $SE = .07$)	$F(1, 43) = 5.789$, $\eta_p^2 = .119$
F4-O1	Individual ($M = .16$, $SE = .11$) vs. social ($M = -.15$, $SE = .08$)	$F(1, 43) = 6.804$, $\eta_p^2 = .137$
F4-P3	Individual ($M = .01$, $SE = .07$) vs. social ($M = -.23$, $SE = .07$)	$F(1, 43) = 5.494$, $\eta_p^2 = .113$
F4-T8	Individual ($M = -.04$, $SE = .1$) vs. social ($M = .33$, $SE = .11$)	$F(1, 43) = 9.914$, $\eta_p^2 = .187$
F7-Fz	Individual ($M = .06$, $SE = .09$) vs. social ($M = .47$, $SE = .11$)	$F(1, 43) = 8.688$, $\eta_p^2 = .168$
F7-P7	Individual ($M = -.19$, $SE = .08$) vs. social ($M = .1$, $SE = .11$)	$F(1, 43) = 7.145$, $\eta_p^2 = .142$
F7-T7	Individual ($M = .67$, $SE = .13$) vs. social ($M = 1.04$, $SE = .14$)	$F(1, 43) = 5.485$, $\eta_p^2 = .113$
F7-T8	Individual ($M = .36$, $SE = .13$) vs. social ($M = -.12$, $SE = .08$)	$F(1, 43) = 11.598$, $\eta_p^2 = .212$
F8-T8	Individual ($M = .68$, $SE = .14$) vs. social ($M = 1.22$, $SE = .13$)	$F(1, 43) = 8.224$, $\eta_p^2 = .161$
Fz-O1	Individual ($M = .04$, $SE = .07$) vs. social ($M = -.26$, $SE = .08$)	$F(1, 43) = 6.806$, $\eta_p^2 = .137$
Fz-P4	Individual ($M = .08$, $SE = .1$) vs. social ($M = -.22$, $SE = .06$)	$F(1, 43) = 7.527$, $\eta_p^2 = .149$
Fz-P8	Individual ($M = .24$, $SE = .09$) vs. social ($M = -.15$, $SE = .08$)	$F(1, 43) = 11.022$, $\eta_p^2 = .204$
Fz-Pz	Individual ($M = .14$, $SE = .08$) vs. social ($M = -.14$, $SE = .07$)	$F(1, 43) = 8.435$, $\eta_p^2 = .164$
Fz-T8	Individual ($M = .17$, $SE = .1$) vs. social ($M = -.14$, $SE = .08$)	$F(1, 43) = 5.337$, $\eta_p^2 = .11$
O1-P4	Individual ($M = -.1$, $SE = .09$) vs. social ($M = .2$, $SE = .1$)	$F(1, 43) = 5.278$, $\eta_p^2 = .109$
P7-T8	Individual ($M = -.21$, $SE = .07$) vs. social ($M = .01$, $SE = .07$)	$F(1, 43) = 5.352$, $\eta_p^2 = .111$
Pz-T7	Individual ($M = -.02$, $SE = .08$) vs. social ($M = -.2$, $SE = .07$)	$F(1, 43) = 4.512$, $\eta_p^2 = .095$

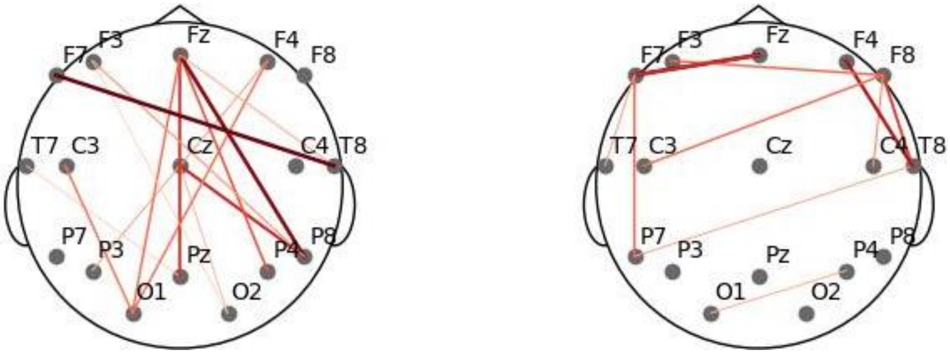


Figure 110: Topography of significant intrabrain comparisons in the alpha band task setting with decreased connectivity (left) and increased connectivity (right). Line thickness correlates with the η_p^2 value.

In the alpha band, the electrode pairs which showed an effect on the n-back level or the interaction of task setting and the n-back level are presented in Table 20.

Table 20: Significant results in intrabrain analysis related to the n-back level in the alpha band.

Electrode	**Descriptives**	**Statistics**
F4-T7	Individual 0-back (*M* = .14, *SE* = .15), and 3-back (*M* = -.09, *SE* = .15), and social 0-back (*M* = -.24, *SE* = .12), and 3-back (*M* = .09, *SE* = .1)	*F*(3, 129) = 3.389, η_p^2 = .073
F7-T7	Individual 0-back (*M* = .7, *SE* = .16) and 2-back (*M* = .39, *SE* = .16), and social 0-back (*M* = .77, *SE* = .19) and 2-back (*M* = 1.25, *SE* = .19)	*F*(3, 129) = 3.241, η_p^2 = .07
F8-Pz	Individual 0-back (*M* = -.21, *SE* = .13), 2-back (*M* = .08, *SE* = .16); social 0-back (*M* = -.02, *SE* = .12), 2-back (*M* = -.14, *SE* = .08)	*F*(3, 129) = 3.302, η_p^2 = .071
P3-Pz	Individual 0-back (*M* = .4, *SE* = .19) and 2-back (*M* = .86, *SE* = .19), and social 0-back (*M* = .31, *SE* = .16).) and 2-back (*M* = .25, *SE* = .13)	*F*(3, 129) = 3.851, η_p^2 = .082
P4-Pz	Individual 0-back (*M* = .24, *SE* = .21) and 2-back (*M* = .44, *SE* = .19), and social 0-back (*M* = .5, *SE* = .16).) and 2-back (*M* = -.06, *SE* = .13)	*F*(3, 129) = 2.806, η_p^2 = .061
C4-O2	0-back (*M* = .16, *SE* = .12) vs. 1-back (*M* = -.21, *SE* = .08) and 3-back (*M* = -.14, *SE* = .08)	*F*(3, 129) = 3.493, η_p^2 = .075
F4-T8	0-back (*M* = .06, *SE* = .11) vs. 3-back (*M* = .41, *SE* = .1)	*F*(3, 129) = 5.098, η_p^2 = .106
F7-P8	0-back (*M* = .16, *SE* = .1) vs. 2-back (*M* = -.13, *SE* = .07)	*F*(3, 129) = 3.52, η_p^2 = .076
O1-P3	0-back (*M* = .22, *SE* = .1) vs. 1-back (*M* = -.12, *SE* = .09)	*F*(3, 129) = 4.099, η_p^2 = .087
O1-T7	0-back (*M* = .14, *SE* = .11) vs. 3-back (*M* = -.12, *SE* = .09)	*F*(3, 129) = 3.896, η_p^2 = .083
O2-P4	0-back (*M* = .45, *SE* = .13), 1-back (*M* = -.04, *SE* = .12) vs. 3-back (*M* = .01, *SE* = .13)	*F*(3, 129) = 5.919, η_p^2 = .121
P3-P7	0-back (*M* = .29, *SE* = .12) vs. 3-back (*M* = -.14, *SE* = .08)	*F*(3, 129) = 4.893, η_p^2 = .102
T7-T8	0-back (*M* = .01, *SE* = .1) vs. 1-back (*M* = .3, *SE* = .1)	*F*(3, 129) = 2.78, η_p^2 = .061

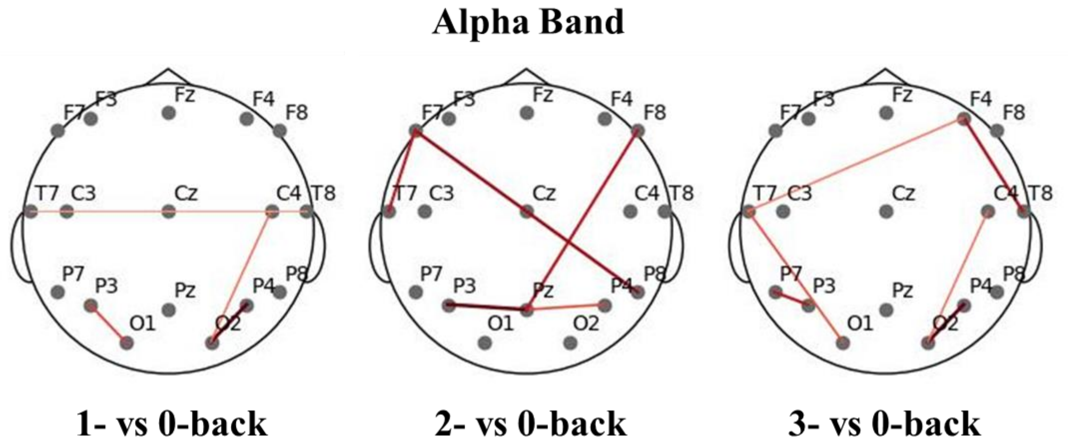


Figure 111: Topography of significant intrabrain connectivity comparisons in the alpha band on n-back levels and interaction of n-back levels with task setting, line thickness correlates with the η_p^2 value.

In the beta band, the electrode pairs which showed an effect on task setting are presented in Table 21.

Table 21: Significant results in intrabrain analysis of individual and social trials in the beta band.

Electrode	**Descriptives**	**Statistics**
C3-F7	Individual (M = .01, SE = .09) vs. social (M = .53, SE = .12)	$F(1, 43) = 15.032$, $\eta_p^2 = .262$
C3-F8	Individual (M = -.08, SE = .08) vs. social (M = .29, SE = .11)	$F(1, 43) = 7.181$, $\eta_p^2 = .143$
C3-O1	Individual (M = .08, SE = .1) vs. social (M = -.2, SE = .07)	$F(1, 43) = 5.047$, $\eta_p^2 = .105$
C3-O2	Individual (M = .1, SE = .1) vs. social (M = -.2, SE = .09)	$F(1, 43) = 4.321$, $\eta_p^2 = .091$
C4-F8	Individual (M = .1, SE = .12) vs. social (M = .46, SE = .1)	$F(1, 43) = 4.388$, $\eta_p^2 = .093$
Cz-P8	Individual (M = -.06, SE = .09) vs. social (M = -.29, SE = .07)	$F(1, 43) = 5.035$, $\eta_p^2 = .105$
F3-F8	Individual (M = -.2, SE = .07) vs. social (M = .16, SE = .09)	$F(1, 43) = 11.673$, $\eta_p^2 = .214$
F3-O2	Individual (M = .16, SE = .12) vs. social (M = -.25, SE = .08)	$F(1, 43) = 6.127$, $\eta_p^2 = .125$
F3-P8	Individual (M = .07, SE = .09) vs. social (M = -.25, SE = .07)	$F(1, 43) = 8.564$, $\eta_p^2 = .166$
F3-T7	Individual (M = -.11, SE = .08) vs. social (M = .24, SE = .1)	$F(1, 43) = 7.955$, $\eta_p^2 = .156$
F3-T8	Individual (M = .01, SE = .08) vs. social (M = -.23, SE = .1)	$F(1, 43) = 7.782$, $\eta_p^2 = .153$
F4-O1	Individual (M = .11, SE = .11) vs. social (M = -.15, SE = .07)	$F(1, 43) = 4.374$, $\eta_p^2 = .092$
F4-T8	Individual (M = -.01, SE = .1) vs. social (M = .33, SE = .1)	$F(1, 43) = 8.095$, $\eta_p^2 = .158$
F7-Fz	Individual (M = .1, SE = .1) vs. social (M = .48, SE = .11)	$F(1, 43) = 7.635$, $\eta_p^2 = .151$
F7-P7	Individual (M = -.17, SE = .07) vs. social (M = .15, SE = .1)	$F(1, 43) = 9.21$, $\eta_p^2 = .176$
F7-T7	Individual (M = .65, SE = .16) vs. social (M = 1.1, SE = .15)	$F(1, 43) = 6.17$, $\eta_p^2 = .125$
F7-T8	Individual (M = .41, SE = .12) vs. social (M = -.18, SE = .08)	$F(1, 43) = 17.896$, $\eta_p^2 = .294$
Fz-P4	Individual (M = .04, SE = .1) vs. social (M = -.29, SE = .07)	$F(1, 43) = 6.121$, $\eta_p^2 = .125$
O1-P4	Individual (M = -.13, SE = .09) vs. social (M = .25, SE = .1)	$F(1, 43) = 10.712$, $\eta_p^2 = .199$
O2-T8	Individual (M = -.19, SE = .06) vs. social (M = .05, SE = .09)	$F(1, 43) = 4.191$, $\eta_p^2 = .089$
Pz-T7	Individual (M = -.02, SE = .06) vs. social (M = -.18, SE = .06)	$F(1, 43) = 4.321$, $\eta_p^2 = .091$
T7-T8	Individual (M = .24, SE = .11) vs. social (M = -.09, SE = .08)	$F(1, 43) = 5.538$, $\eta_p^2 = .114$

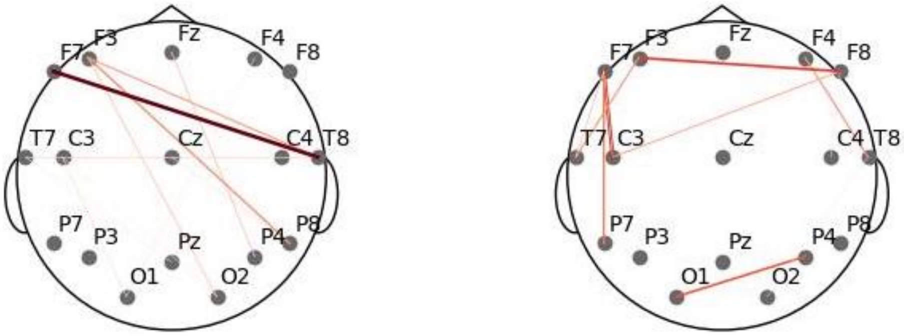
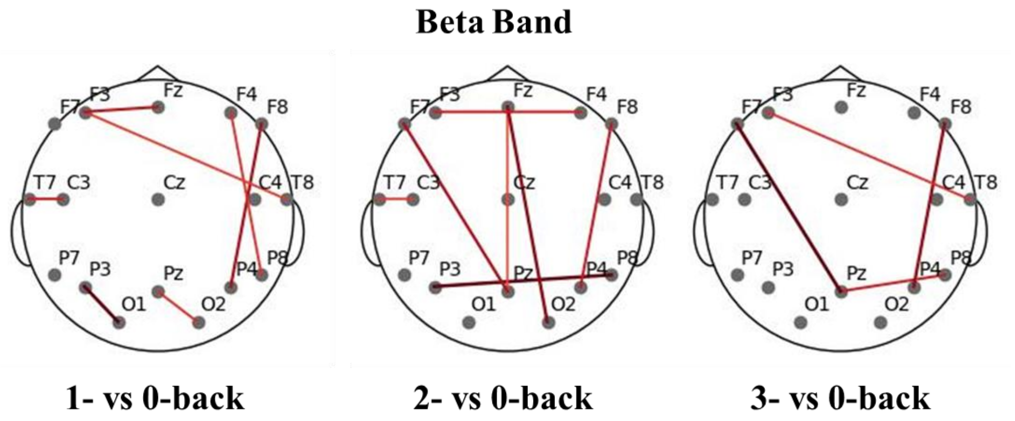


Figure 112: Topography of significant intrabrain comparisons in the beta band task setting with decreased connectivity (left) and increased connectivity (right). Line thickness correlates with the η_p^2 value.

In the beta band, the electrode pairs which showed an effect on the n-back level or the interaction of task setting and the n-back level are presented in Table 22.

Table 22: Significant results in intrabrain analysis related to the n-back level in the beta band.

Electrode	**Descriptives**	**Statistics**
C3-T7	Individual 0-back (*M* = .17, *SE* = .15), 1-back (*M* = -.04, *SE* = .15), and 2-back (*M* = -.04, *SE* = .14), and social 0-back (*M* = -.11, *SE* = .14), 1-back (*M* = .24, *SE* = .13), and 2-back (*M* = .24, *SE* = .14)	*F*(3, 129) = 2.946, η_p^2 = .064
F3-F4	Individual 0-back (*M* = .23, *SE* = .16) and 2-back (*M* = -.3, *SE* = .1), and social 0-back (*M* = .02, *SE* = .14), and 2-back (*M* = .27, *SE* = .16)	*F*(3, 129) = 3.243, η_p^2 = .07
F3-Fz	Individual 0-back (*M* = .58, *SE* = .19) and 1-back (*M* = .19, *SE* = .16), and social 0-back (*M* = .24, *SE* = .15), and 1-back (*M* = .64, *SE* = .16)	*F*(3, 129) = 3.21, η_p^2 = .069
F3-T8	Individual 0-back (*M* = .29, *SE* = .14), 1-back (*M* = -.08, *SE* = .13) and 3-back (*M* = -.05, *SE* = .13), and social 0-back (*M* = -.35, *SE* = .11), 1-back (*M* = -.15, *SE* = .12) and 3-back (*M* = -.11, *SE* = .12)	*F*(3, 129) = 2.701, η_p^2 = .059
F7-Pz	Individual 0-back (*M* = -.3, *SE* = .1), 2-back (*M* = .11, *SE* = .15) and 3-back (*M* = .18, *SE* = .13), and social 0-back (*M* = -.03, *SE* = .12), 2-back (*M* = -.14, *SE* = .14) and 3-back (*M* = -.16, *SE* = .11)	*F*(3, 129) = 3.576, η_p^2 = .077
F8-P4	Individual 0-back (*M* = -.49, *SE* = .12), 1-back (*M* = -.15, *SE* = .13), 2-back (*M* = -.17, *SE* = .12) and 3-back (*M* = -.12, *SE* = .11), and social 0-back (*M* = .12, *SE* = .12), 1-back (*M* = -.2, *SE* = .11), 2-back (*M* = -.03, *SE* = .11) and 3-back (*M* = .05, *SE* = .12)	*F*(3, 129) = 3.348, η_p^2 = .072
O2-Pz	Individual 0-back (*M* = -.15, *SE* = .14) and 1-back (*M* = .17, *SE* = .15), and social 0-back (*M* = -.04, *SE* = .12) and 1-back (*M* = -.16, *SE* = .1)	*F*(3, 129) = 2.783, η_p^2 = .061
F4-P8	0-back (*M* = -.21, *SE* = .08) vs. 1-back (*M* = .11, *SE* = .11)	*F*(3, 129) = 2.775, η_p^2 = .061
Fz-O2	0-back (*M* = -.22, *SE* = .09) vs. 2-back (*M* = .12, *SE* = .1)	*F*(3, 129) = 3.863, η_p^2 = .082
Fz-Pz	0-back (*M* = -.21, *SE* = .08) vs. 2-back (*M* = .09, *SE* = .11)	*F*(3, 129) = 2.805, η_p^2 = .061
O1-P3	0-back (*M* = .24, *SE* = .12) vs. 1-back (*M* = -.14, *SE* = .09)	*F*(3, 129) = 3.768, η_p^2 = .081
P3-P8	0-back (*M* = -.36, *SE* = .08) vs. 2-back (*M* = -.01, *SE* = .09) and 3-back (*M* = .08, *SE* = .07)	*F*(3, 129) = 4.112, η_p^2 = .087
P8-Pz	0-back (*M* = -.25, *SE* = .08) vs. 3-back (*M* = .02, *SE* = .1)	*F*(3, 129) = 2.874, η_p^2 = .063



1- vs 0-back

2- vs 0-back

3- vs 0-back

Figure 113: Topography of significant intrabrain connectivity comparisons in the beta band on n-back levels and interaction of n-back levels with task setting, line thickness correlates with the η_p^2 value.

In the delta band, the electrode pairs which showed an effect on task setting are presented in Table 23.

Table 23: Significant results in intrabrain analysis of individual and social trials in the delta band.

Electrode	**Descriptives**	**Statistics**
C3-F7	Individual (*M* = .04, *SE* = .09) vs. social (*M* = .49, *SE* = .1)	*F*(1, 43) = 14.273, η_p^2 = .249
C3-F8	Individual (*M* = -.06, *SE* = .07) vs. social (*M* = .34, *SE* = .1)	*F*(1, 43) = 9.674, η_p^2 = .184
C3-Fz	Individual (*M* = .01, *SE* = .08) vs. social (*M* = .27, *SE* = .08)	*F*(1, 43) = 5.366, η_p^2 = .111
C3-O1	Individual (*M* = .2, *SE* = .11) vs. social (*M* = -.2, *SE* = .07)	*F*(1, 43) = 10.846, η_p^2 = .201
C3-O2	Individual (*M* = .08, *SE* = .1) vs. social (*M* = -.23, *SE* = .09)	*F*(1, 43) = 4.75, η_p^2 = .099
C3-P8	Individual (*M* = .07, *SE* = .1) vs. social (*M* = -.24, *SE* = .09)	*F*(1, 43) = 5.984, η_p^2 = .122
C4-F3	Individual (*M* = .04, *SE* = .09) vs. social (*M* = -.16, *SE* = .07)	*F*(1, 43) = 4.173, η_p^2 = .088
C4-F4	Individual (*M* = .24, *SE* = .11) vs. social (*M* = .52, *SE* = .09)	*F*(1, 43) = 4.95, η_p^2 = .103
C4-F8	Individual (*M* = .18, *SE* = .11) vs. social (*M* = .52, *SE* = .1)	*F*(1, 43) = 4.488, η_p^2 = .095
C4-T8	Individual (*M* = .1, *SE* = .1) vs. social (*M* = .51, *SE* = .11)	*F*(1, 43) = 7.947, η_p^2 = .156
Cz-O2	Individual (*M* = -.03, *SE* = .09) vs. social (*M* = -.27, *SE* = .08)	*F*(1, 43) = 4.328, η_p^2 = .091
Cz-P8	Individual (*M* = -.01, *SE* = .09) vs. social (*M* = -.38, *SE* = .06)	*F*(1, 43) = 11.037, η_p^2 = .204
F3-F4	Individual (*M* = -.15, *SE* = .07) vs. social (*M* = .22, *SE* = .09)	*F*(1, 43) = 13.669, η_p^2 = .241
F3-F8	Individual (*M* = -.08, *SE* = .07) vs. social (*M* = .16, *SE* = .1)	*F*(1, 43) = 4.773, η_p^2 = .1
F3-O2	Individual (*M* = .15, *SE* = .1) vs. social (*M* = -.19, *SE* = .06)	*F*(1, 43) = 7.905, η_p^2 = .155
F3-P8	Individual (*M* = .08, *SE* = .1) vs. social (*M* = -.2, *SE* = .07)	*F*(1, 43) = 5.386, η_p^2 = .111
F3-T7	Individual (*M* = .05, *SE* = .08) vs. social (*M* = .3, *SE* = .1)	*F*(1, 43) = 4.915, , η_p^2 = .103
F3-T8	Individual (*M* = .14, *SE* = .1) vs. social (*M* = -.21, *SE* = .07)	*F*(1, 43) = 9.552, η_p^2 = .182
F4-F7	Individual (*M* = -.14, *SE* = .07) vs. social (*M* = .13, *SE* = .09)	*F*(1, 43) = 5.191, η_p^2 = .108
F4-F8	Individual (*M* = .82, *SE* = .13) vs. social (*M* = 1.3, *SE* = .11)	*F*(1, 43) = 7.381, η_p^2 = .147
F4-T8	Individual (*M* = -.1, *SE* = .1) vs. social (*M* = .43, *SE* = .11)	*F*(1, 43) = 21.799, η_p^2 = .336
F7-T7	Individual (*M* = .62, *SE* = .12) vs. social (*M* = .97, *SE* = .12)	*F*(1, 43) = 5.204, η_p^2 = .108
F7-T8	Individual (*M* = .53, *SE* = .13) vs. social (*M* = -.08, *SE* = .08)	*F*(1, 43) = 17.062, η_p^2 = .284
F8-T8	Individual (*M* = .69, *SE* = .12) vs. social (*M* = 1.17, *SE* = .11)	*F*(1, 43) = 9.517, η_p^2 = .181

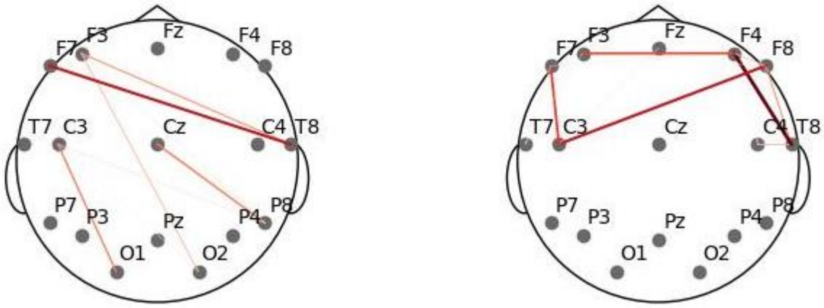
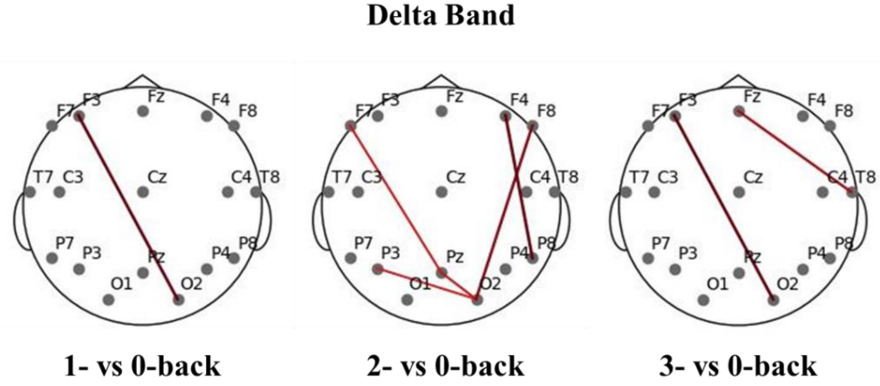


Figure 114: Topography of significant intrabrain comparisons in the delta band task setting with decreased connectivity (left) and increased connectivity (right). Line thickness correlates with the η_p^2 value.

In the delta band, the electrode pairs which showed an effect on the n-back level or the interaction of task setting and the n-back level are presented in Table 24.

Table 24: Significant results in intrabrain analysis related to the n-back level in the delta band.

Electrode	Descriptives	Statistics
F4-P8	Individual 0-back (M = -.15, SE = .11), 2-back (M = -.28, SE = .1) and social 0-back (M = -.05, SE = .11), 2-back (M = .23, SE = .14)	$F(3, 129) = 3.819$, $\eta_p^2 = .082$
F7-Pz	Individual 0-back (M = -.03, SE = .12), 2-back (M = .3, SE = .16) and social 0-back (M = -.01, SE = .14), 2-back (M = -.17, SE = .13)	$F(3, 129) = 3.107$, $\eta_p^2 = .067$
F8-O2	Individual 0-back (M = -.02, SE = .11), 2-back (M = .11, SE = .11) and social 0-back (M = .06, SE = .12), 2-back (M = -.31, SE = .1)	$F(3, 129) = 3.652$, $\eta_p^2 = .078$
Fz-T8	Individual 0-back (M = .18, SE = .14), 3-back (M = -.35, SE = .12) and social 0-back (M = -.14, SE = .13), 3-back (M = .13, SE = .13)	$F(3, 129) = 3.608$, $\eta_p^2 = .077$
F3-O2	0-back (M = .2, SE = .09) vs. 1-back (M = -.18, SE = .11) and 3-back (M = -.13, SE = .08)	$F(3, 129) = 4$, $\eta_p^2 = .085$
O2-P3	0-back (M = -.22, SE = .09) vs. 2-back (M = .14, SE = .08)	$F(3, 129) = 3.014$, $\eta_p^2 = .066$
O2-Pz	0-back (M = -.13, SE = .11) vs. 2-back (M = .18, SE = .09) and 3-back (M = .18, SE = .08)	$F(3, 129) = 3.122$, $\eta_p^2 = .068$



1- vs 0-back

2- vs 0-back

3- vs 0-back

Figure 115: Topography of significant intrabrain connectivity comparisons in the delta band on n-back levels and interaction of n-back levels with task setting, line thickness correlates with the η_p^2 value.

In the gamma band, the electrode pairs which showed an effect on task setting are presented in Table 25.

Table 25: Significant results in intrabrain analysis of individual and social trials in the gamma band.

Elec-trode	**Descriptives**	**Statistics**
C3-F7	Individual (M = -.05, SE = .09) vs. social (M = .44, SE = .13)	$F(1, 43) = 9.314$, $\eta_p^2 = .178$
C3-F8	Individual (M = -.08, SE = .09) vs. social (M = .27, SE = .11)	$F(1, 43) = 6.268$, $\eta_p^2 = .127$
C3-O1	Individual (M = .17, SE = .09) vs. social (M = -.14, SE = .07)	$F(1, 43) = 7.979$, $\eta_p^2 = .157$
C3-O2	Individual (M = .12, SE = .11) vs. social (M = -.21, SE = .09)	$F(1, 43) = 4.242$, $\eta_p^2 = .09$
C3-P8	Individual (M = .06, SE = .09) vs. social (M = -.2, SE = .08)	$F(1, 43) = 6.14$, $\eta_p^2 = .125$
C4-F8	Individual (M = .03, SE = .11) vs. social (M = .44, SE = .1)	$F(1, 43) = 6.88$, $\eta_p^2 = .138$
C4-T8	Individual (M = .04, SE = .09) vs. social (M = .32, SE = .11)	$F(1, 43) = 4.508$, $\eta_p^2 = .095$
Cz-P8	Individual (M = -.07, SE = .08) vs. social (M = -.28, SE = .06)	$F(1, 43) = 7.117$, $\eta_p^2 = .142$
F3-F8	Individual (M = -.2, SE = .07) vs. social (M = .23, SE = .09)	$F(1, 43) = 13.236$, $\eta_p^2 = .235$
F3-T8	Individual (M = .06, SE = .09) vs. social (M = -.18, SE = .07)	$F(1, 43) = 4.459$, $\eta_p^2 = .094$
F4-P3	Individual (M = .04, SE = .09) vs. social (M = -.25, SE = .07)	$F(1, 43) = 5.554$, $\eta_p^2 = .114$
F4-T8	Individual (M = -.06, SE = .08) vs. social (M = .34, SE = .11)	$F(1, 43) = 14.147$, $\eta_p^2 = .248$
F7-Fz	Individual (M = .06, SE = .09) vs. social (M = .36, SE = .11)	$F(1, 43) = 4.813$, $\eta_p^2 = .101$
F7-P7	Individual (M = -.27, SE = .05) vs. social (M = .14, SE = .1)	$F(1, 43) = 14.06$, $\eta_p^2 = .246$
F7-T7	Individual (M = .5, SE = .14) vs. social (M = .98, SE = .14)	$F(1, 43) = 7.734$, $\eta_p^2 = .152$
F7-T8	Individual (M = .27, SE = .14) vs. social (M = -.09, SE = .09)	$F(1, 43) = 4.547$, $\eta_p^2 = .096$
F8-P8	Individual (M = -.03, SE = .09) vs. social (M = .29, SE = .11)	$F(1, 43) = 6.031$, $\eta_p^2 = .123$
F8-T8	Individual (M = .71, SE = .15) vs. social (M = 1.16, SE = .14)	$F(1, 43) = 5.272$, $\eta_p^2 = .109$
Fz-P4	Individual (M = .1, SE = .1) vs. social (M = -.24, SE = .07)	$F(1, 43) = 6.389$, $\eta_p^2 = .129$
Fz-P8	Individual (M = .13, SE = .07) vs. social (M = -.18, SE = .07)	$F(1, 43) = 11.19$, $\eta_p^2 = .207$
Fz-Pz	Individual (M = .07, SE = .09) vs. social (M = -.16, SE = .07)	$F(1, 43) = 5.788$, $\eta_p^2 = .119$
P3-T8	Individual (M = -.01, SE = .08) vs. social (M = -.23, SE = .06)	$F(1, 43) = 8.317$, $\eta_p^2 = .162$
P4-T8	Individual (M = -.17, SE = .08) vs. social (M = .09, SE = .08)	$F(1, 43) = 6.209$, $\eta_p^2 = .126$
P8-Pz	Individual (M = .08, SE = .06) vs. social (M = -.17, SE = .09)	$F(1, 43) = 9.93$, $\eta_p^2 = .188$
Pz-T7	Individual (M = -.01, SE = .06) vs. social (M = -.19, SE = .06)	$F(1, 43) = 4.29$, $\eta_p^2 = .091$

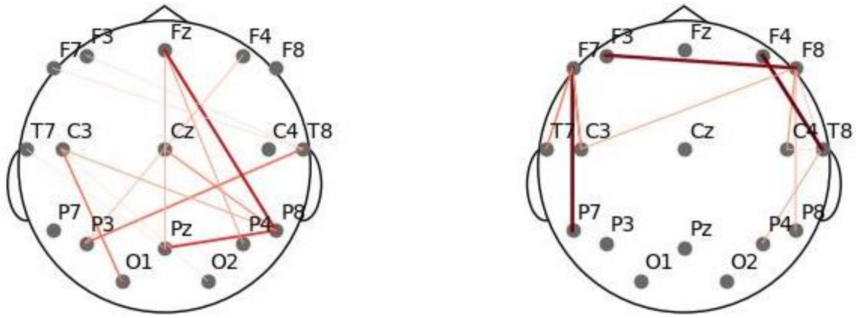
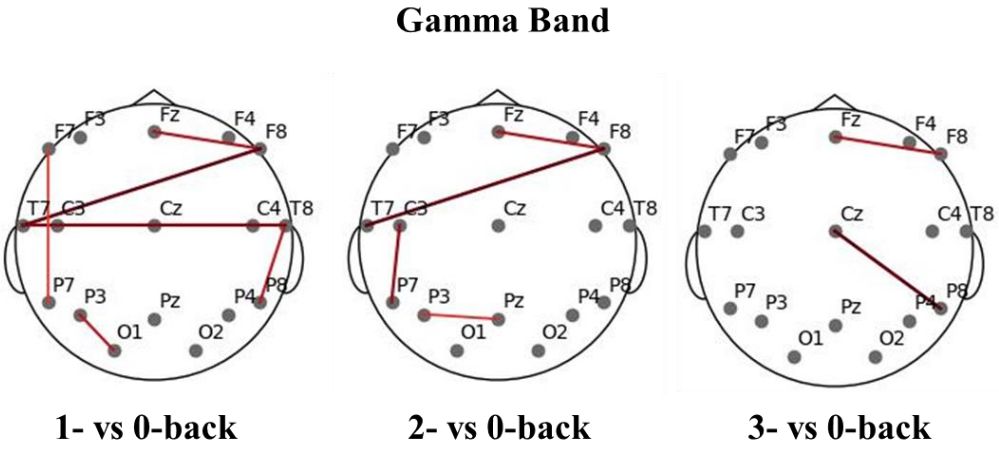


Figure 116: Topography of significant intrabrain comparisons in the gamma band on task setting with decreased connectivity (left) and increased connectivity (right). Line thickness correlates with the η_p^2 value.

In the gamma band, the electrode pairs which showed an effect on the n-back level or the interaction of task setting and the n-back level are presented in Table 26.

Table 26: Significant results in intrabrain analysis related to the n-back level in the gamma band.

Elec-trode	**Descriptives**	**Statistics**
C3-P7	Individual 0-back (*M* = .17, *SE* = .12), 2-back (*M* = -.26, *SE* = .11), social 0-back (*M* = -.12, *SE* = .13), 2-back (*M* = .02, *SE* = .13)	*F*(3, 129) = 3.421, $p < .05$, $\eta_p^2 = .074$
P3-Pz	Individual 0-back (*M* = .42, *SE* = .2), 2-back (*M* = .67, *SE* = .19), social 0-back (*M* = .43, *SE* = .16), 2-back (*M* = .05, *SE* = .14)	*F*(3, 129) = 2.773, $\eta_p^2 = .061$
Cz-P8	0-back (*M* = -.34, *SE* = .08) and 3-back (*M* = .02, *SE* = .1)	*F*(3, 129) = 3.844, $\eta_p^2 = .082$
F7-P7	0-back (*M* = .12, *SE* = .09) and 1-back (*M* = -.22, *SE* = .09)	*F*(3, 129) = 2.812, $\eta_p^2 = .061$
F8-Fz	0-back (*M* = -.19, *SE* = .07), 1-back (*M* = .08, *SE* = .09), 2-back (*M* = .09, *SE* = .1), 3-back (*M* = .03, *SE* = .09)	*F*(3, 129) = 3.298, $\eta_p^2 = .071$
F8-T7	0-back (*M* = -.24, *SE* = .08), 1-back (*M* = .08, *SE* = .11), 2-back (*M* = .11, *SE* = .1)	*F*(3, 129) = 3.784, $\eta_p^2 = .081$
O1-P3	0-back (*M* = .21, *SE* = .12) and 1-back (*M* = -.13, *SE* = .11)	*F*(3, 129) = 3.181, $\eta_p^2 = .069$
P8-T8	0-back (*M* = .59, *SE* = .14) and 1-back (*M* = 1.01, *SE* = .15)	*F*(3, 129) = 3.204, $\eta_p^2 = .069$
T7-T8	0-back (*M* = -.09, *SE* = .11) and 1-back (*M* = .22, *SE* = .1)	*F*(3, 129) = 3.587, $\eta_p^2 = .077$


Gamma Band

1- vs 0-back **2- vs 0-back** **3- vs 0-back**

Figure 117: Topography of significant intrabrain connectivity comparisons in the gamma band on n-back levels and interaction of n-back levels with task setting, line thickness correlates with the η_p^2 value.

In the theta band, the electrode pairs which showed an effect on task setting are presented in Table 27.

Table 27: Significant results in intrabrain analysis of individual and social trials in the theta band.

Electrode	Descriptives	Statistics
C3-F7	Individual (*M* = .01, *SE* = .09) vs. social (*M* = .45, *SE* = .11)	*F*(1, 43) = 12.399, η_p^2 = .224
C3-F8	Individual (*M* = -.12, *SE* = .06) vs. social (*M* = .36, *SE* = .1)	*F*(1, 43) = 18.332, η_p^2 = .299
C3-O1	Individual (*M* = .07, *SE* = .11) vs. social (*M* = -.24, *SE* = .07)	*F*(1, 43) = 7.05, η_p^2 = .141
Cz-P8	Individual (*M* = .02, *SE* = .1) vs. social (*M* = -.26, *SE* = .08)	*F*(1, 43) = 6.525, η_p^2 = .132
F3-F4	Individual (*M* = -.15, *SE* = .08) vs. social (*M* = .23, *SE* = .09)	*F*(1, 43) = 11.081, η_p^2 = .205
F3-F8	Individual (*M* = -.2, *SE* = .08) vs. social (*M* = .21, *SE* = .1)	*F*(1, 43) = 10.949, η_p^2 = .203
F3-O2	Individual (*M* = .13, *SE* = .09) vs. social (*M* = -.22, *SE* = .07)	*F*(1, 43) = 7.229, η_p^2 = .144
F3-P8	Individual (*M* = .03, *SE* = .09) vs. social (*M* = -.22, *SE* = .07)	*F*(1, 43) = 5.741, η_p^2 = .118
F3-T8	Individual (*M* = -.01, *SE* = .08) vs. social (*M* = -.2, *SE* = .07)	*F*(1, 43) = 4.484, η_p^2 = .094
F4-F7	Individual (*M* = -.19, *SE* = .08) vs. social (*M* = .12, *SE* = .09)	*F*(1, 43) = 6.387, η_p^2 = .129
F4-P3	Individual (*M* = .05, *SE* = .09) vs. social (*M* = -.26, *SE* = .08)	*F*(1, 43) = 6.241, η_p^2 = .127
F4-Pz	Individual (*M* = -.04, *SE* = .08) vs. social (*M* = -.27, *SE* = .07)	*F*(1, 43) = 4.42, η_p^2 = .093
F4-T8	Individual (*M* = .09, *SE* = .1) vs. social (*M* = .38, *SE* = .12)	*F*(1, 43) = 5.325, η_p^2 = .11
F7-Fz	Individual (*M* = .09, *SE* = .1) vs. social (*M* = .45, *SE* = .11)	*F*(1, 43) = 8.774, η_p^2 = .169
F7-P7	Individual (*M* = -.15, *SE* = .07) vs. social (*M* = .12, *SE* = .1)	*F*(1, 43) = 8.276, η_p^2 = .161
F7-T7	Individual (*M* = .61, *SE* = .14) vs. social (*M* = 1.03, *SE* = .14)	*F*(1, 43) = 5.726, η_p^2 = .118
F7-T8	Individual (*M* = .4, *SE* = .13) vs. social (*M* = -.12, *SE* = .08)	*F*(1, 43) = 11.415, η_p^2 = .21
F8-T8	Individual (*M* = .79, *SE* = .14) vs. social (*M* = 1.24, *SE* = .13)	*F*(1, 43) = 5.356, η_p^2 = .111
Fz-O1	Individual (*M* = .04, *SE* = .07) vs. social (*M* = -.21, *SE* = .1)	*F*(1, 43) = 4.946, η_p^2 = .103
Fz-P4	Individual (*M* = .09, *SE* = .1) vs. social (*M* = -.21, *SE* = .08)	*F*(1, 43) = 6.275, η_p^2 = .127
Fz-P8	Individual (*M* = .21, *SE* = .1) vs. social (*M* = -.09, *SE* = .09)	*F*(1, 43) = 5.317, η_p^2 = .11
O1-P4	Individual (*M* = -.09, *SE* = .09) vs. social (*M* = .19, *SE* = .1)	*F*(1, 43) = 5.278, η_p^2 = .109
T7-T8	Individual (*M* = .29, *SE* = .12) vs. social (*M* = -.06, *SE* = .09)	*F*(1, 43) = 5.596, η_p^2 = .115

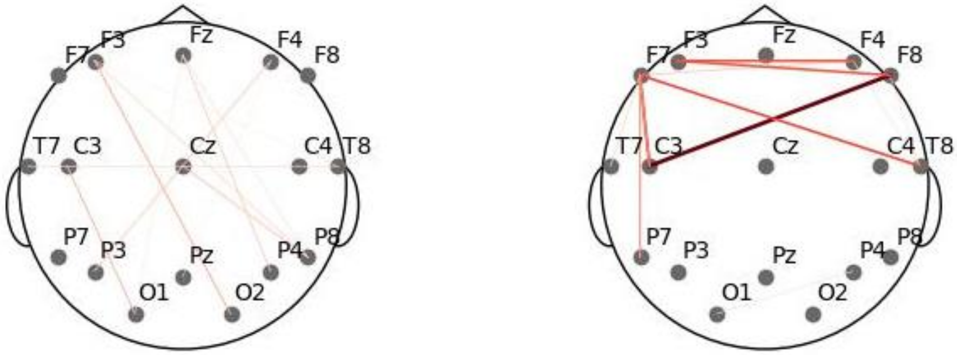
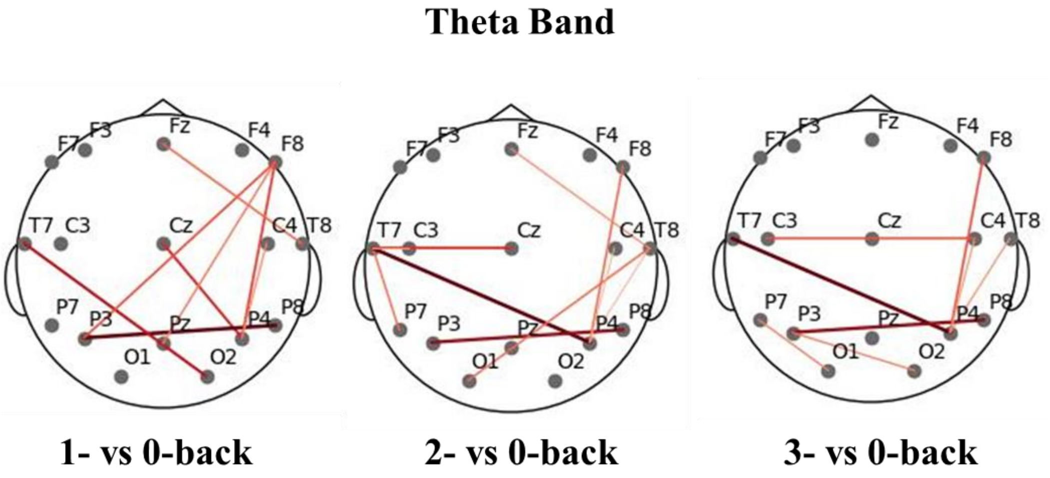


Figure 118: Topography of significant intrabrain comparisons in the theta band on task setting with decreased connectivity (left) and increased connectivity (right). Line thickness correlates with the η_p^2 value.

In the theta band, the electrode pairs which showed an effect on the n-back level or the interaction of task setting and the n-back level are presented in Table 28.

Table 28: Significant results in intrabrain analysis related to the n-back level in the theta band.

Electrode	**Descriptives**	**Statistics**
C3-C4	Individual 0-back ($M = .18$, $SE = .17$), 3-back ($M = -.1$, $SE = .14$) and social 0-back ($M = .03$, $SE = .12$), 3-back ($M = .47$, $SE = .16$)	$F(3, 129) = 3.57$, $\eta_p^2 = .077$
C3-T7	Individual 0-back ($M = .29$, $SE = .18$), 2-back ($M = -.11$, $SE = .11$) and social 0-back ($M = -.05$, $SE = .14$), 2-back ($M = .26$, $SE = .16$)	$F(3, 129) = 2.924$, $\eta_p^2 = .064$
C4-P4	Individual 0-back ($M = -.17$, $SE = .15$), 1-back ($M = .16$, $SE = .15$), 2-back ($M = .24$, $SE = .14$), 3-back ($M = .3$, $SE = .15$) and social 0-back ($M = .51$, $SE = .16$), 1-back ($M = .27$, $SE = .16$), 2-back ($M = .32$, $SE = .14$), 3-back ($M = .39$, $SE = .15$)	$F(3, 129) = 2.767$, $\eta_p^2 = .06$
Cz-P4	Individual 0-back ($M = -.14$, $SE = .14$), 1-back ($M = .11$, $SE = .13$) and social 0-back ($M = .1$, $SE = .15$), 1-back ($M = -.33$, $SE = .12$)	$F(3, 129) = 3.839$, $\eta_p^2 = .082$
Cz-T7	Individual 0-back ($M = .02$, $SE = .12$), 2-back ($M = -.27$, $SE = .11$) and social 0-back ($M = -.04$, $SE = .13$), 2-back ($M = .09$, $SE = .14$)	$F(3, 129) = 4.185$, $\eta_p^2 = .089$
F8-P4	Individual 0-back ($M = -.37$, $SE = .12$), 1-back ($M = .01$, $SE = .15$), 2-back ($M = -.07$, $SE = .12$), 3-back ($M = -.05$, $SE = .1$) and social 0-back ($M = .14$, $SE = .13$), 1-back ($M = -.19$, $SE = .11$), 2-back ($M = -.08$, $SE = .11$), 3-back ($M = -.07$, $SE = .13$)	$F(3, 129) = 3.608$, $\eta_p^2 = .077$
Fz-T8	Individual 0-back ($M = .38$, $SE = .16$), 1-back ($M = -.03$, $SE = .14$), 2-back ($M = .12$, $SE = .14$) and social setting 0-back ($M = -.23$, $SE = .12$), 1-back ($M = -.02$, $SE = .13$), 2-back ($M = .03$, $SE = .15$)	$F(3, 129) = 3.162$, $\eta_p^2 = .068$
P4-T8	Individual 0-back ($M = -.26$, $SE = .11$), 2-back ($M = -.14$, $SE = .12$), 3-back ($M = .1$, $SE = .11$) and social 0-back ($M = .27$, $SE = .13$), 2-back ($M = -.02$, $SE = .11$), 3-back ($M = .11$, $SE = .11$)	$F(3, 129) = 2.725$, $p < .05$, $\eta_p^2 = .06$
O2-T7	Individual 0-back ($M = .13$, $SE = .13$), 1-back ($M = -.24$, $SE = .12$) and social 0-back ($M = -.11$, $SE = .15$), 1-back ($M = .14$, $SE = .14$)	$F(3, 129) = 4.22$, $\eta_p^2 = .089$
F8-P3	0-back ($M = -.1$, $SE = .09$) and 1-back ($M = .19$, $SE = .12$)	$F(3, 129) = 3.372$, $\eta_p^2 = .073$
F8-Pz	0-back ($M = -.19$, $SE = .08$) and 1-back ($M = .09$, $SE = .09$)	$F(3, 129) = 2.962$, $\eta_p^2 = .064$
O1-P7	0-back ($M = .41$, $SE = .13$) and 3-back ($M = .1$, $SE = .12$)	$F(3, 129) = 2.975$, $\eta_p^2 = .065$
O1-T8	0-back ($M = .14$, $SE = .09$) and 2-back ($M = -.24$, $SE = .08$)	$F(3, 129) = 3.524$, $\eta_p^2 = .076$
O2-P3	0-back ($M = -.3$, $SE = .08$) and 3-back ($M = -.1$, $SE = .08$)	$F(3, 129) = 2.967$, $\eta_p^2 = .065$
P3-P8	0-back ($M = -.47$, $SE = .07$), 1-back ($M = -.18$, $SE = .09$), 2-back ($M = -.11$, $SE = .07$), and 3-back ($M = -.19$, $SE = .09$)	$F(3, 129) = 5.104$, $\eta_p^2 = .106$
P4-T7	0-back ($M = -.21$, $SE = .09$), 2-back ($M = .17$, $SE = .09$), and 3-back ($M = .22$, $SE = .09$)	$F(3, 129) = 5.546$, $\eta_p^2 = .114$
P7-T7	0-back ($M = .17$, $SE = .12$) and 2-back ($M = .53$, $SE = .11$)	$F(3, 129) = 3.467$, $\eta_p^2 = .075$



1- vs 0-back

2- vs 0-back

3- vs 0-back

Figure 119: Topography of significant intrabrain connectivity comparisons in the theta band on n-back levels and interaction of n-back levels with task setting, line thickness correlates with the η_p^2 value.

CHAPTER 5

DISCUSSION

This study evaluated the differences between individual and social versions of the n-back task with behavioral measures and analyses of EEG, ECG, EOG and fNIRS data, including hyperscanning of EEG and fNIRS recordings and assessment of event related potentials on EEG data. Personality traits of the participants were taken into consideration regarding their extraversion.

None of the measures indicated a strong correlation between the outcome and task type (following the letter or the place), which condition the participant started with (first individual condition or first social condition), or gender of the dyad. This suggests that the experimental procedure of starting with the individual condition of the first participant, then having both participants perform the social condition, and finishing with the individual condition of the second participant was a viable method, and letter-following and place-following n-back paradigms were compatible for using simultaneously.

5.1. The Effect of the n-back Level

The analyses regarding the effect of n-back level on behavioral, physiological and neural measures provided the following results:

- Behavioral performance was similar to the literature on the n-back paradigm (Finc et al., 2020; Herff et al., 2014; Hill et al., 2019; Hjortkjær et al., 2020), as the difficulty of the n-back level increased, there was an increase in reaction times, the number of missed trials, and the number of wrong responses; whereas d' scores decreased.

- Heart rate increase (Wilson, 2002) and Heart Rate Variability decrease (Matthews et al., 2015) were in support of the behavioral indicators that participants found 2- and 3-back levels more difficult than 0- and 1-back, as expected and similar to a previous study (Mandrick et al., 2016).

- Assessment of fNIRS data indicated that recordings from PFC reflected high mental effort caused by the increase in n-back level, which is in line with the literature (Durantin et al., 2014; Owen et al., 2005; Pessoa, 2013).

- The EEG power spectrum analysis revealed an increase in theta power across midline electrodes, in line with the literature (Berka et al., 2007).

- A late negative component was measured in C4 during wrong responses in 2-back and 3-back levels, which might be linked to response selection conflict (Larson et al., 2014).

- There was no effect of the n-back level on any of the EOG measures.

- Interbrain coherence measured in fNIRS and EEG changed with the n-back level.

- The most salient effect of n-back level on intrabrain coherence was detected at HbR measure of fNIRS, which showed right lateralization. HbO measure and EEG analysis revealed small effects.

The parallel between the results of the analysis of the comparisons regarding n-back levels indicated that laboratory setting and devices used in the study were adequate, and participants did not state any problems regarding the devices, the n-back paradigm or the current way of counterbalancing the order of the conditions (i.e., individual for the first participant, social condition, individual for the second participant). The analysis of reaction times, missed trials and wrong responses suggested that all participants except two understood the task.

Wavelet Transform Coherence in fNIRS were observed to increase as participants moved to higher n-back levels. However, this effect was lost in 3-back, probably due to the task getting too difficult to track the other participant's effort. In the study, the n-back levels always came in the same order, starting with the easiest and ending with the hardest: 0-back, then 1-back, then 2-back, and finally 3-back. So, even though the increase in the first blocks could be explained with the effect of time, this cannot explain the drop seen in 3-back. Therefore, it is more likely that the increase in WTC is due to participants sharing the task until they are forced to focus only on their own. This finding is in line with the growing literature on wavelet transform coherence during joint action that interbrain connectivity is observed among prefrontal cortex regions of co-actors (X. Cui et al., 2012; Reindl et al., 2018; Toppi et al., 2016). DLPFC is the most often reported subregion in the PFC for this effect, but other areas such as Inferior Frontal Gyrus, Superior Frontal Gyrus, or Frontopolar cortex also show increase in interbrain connectivity during various cooperative tasks (Czeszumski et al., 2022; Kruppa et al., 2021). A previous study also argued that in the event of failure during cooperation, the synchrony is lost and synergic activity breaks down (Balconi, Vanutelli, et al., 2018). Intrabrain coherence also showed significant differences around right DLPFC.

Another explanation for the decrease in wavelet transform coherence values at the 3-back level could be that the interbrain connectivity was depleting over time, as it has been reported in the literature previously (Dikker et al., 2021; Reinero et al., 2021). However, these studies featured longer experiments and the decrease in WTC reportedly occurred later than the duration of this study. In this study, each block lasted 75 seconds with a 10 seconds long interval in between each block, which is not long enough to observe this reported drop over time in WTC. Therefore, losing track of the companion's action during the more difficult task blocks is still the more likely explanation for the loss of interbrain connectivity measured in this study.

The interbrain connectivity analysis in this study showed significant differences in every frequency band, and in general, the effects were distributed over the scalp. It could be noted there was a difference between the number of electrode pairs with significant differences in the following bands: The number of significant differences decreased in the lower frequencies (Delta and Theta), whereas it increased in the Beta band. In the literature, delta and theta coherence is related to cognitive synchronization and joint action (Balconi & Angioletti, 2023; Bolt & Loehr, 2021; Dumas et al., 2010; Moreau et al., 2022), so the decrease in these bands, taken into consideration with fNIRS results in the same line, can be regarded as a sign of detachment from the co-representation of the task in lower difficulties to focusing on one's own task at the 3-back level, and the increase in the beta band which is associated with social closeness (Dikker et al., 2021) as a hint of social facilitation. In a meta-analysis of 24 n-back studies with neuroimaging, posterior parietal cortex was suggested as an important region for rehearsal of items in working memory (Owen et al., 2005), which might explain the findings in this study regarding the parietal cortex as well.

In the EEG hyperscanning analysis of this study, a small number of significant comparisons were detected between the occipital cortex and frontal, temporal, central, and parietal areas. Occipital cortex is generally associated with visual processing, visual object perception, and understanding the emotions of others (Abassi & Papeo, 2020; Labbe et al., 2020; Patel et al., 2023). A meta-analysis (Martins et al., 2021) reported that the occipital cortex is involved in a wide cortical network which evaluates social rewards and punishments as well. Another meta-analysis (Du et al., 2021) indicated that the parietal cortex and the occipital cortex are involved in attention shifts regarding spatial and social knowledge. One study linked social communication deficits in the autism spectrum disorder to the occipital cortex (Jung et al., 2019).

Connectivity between frontal and occipital cortex has been suggested to regulate attention under anxiety (K. Li et al., 2020), whereas connectivity between temporal and occipital regions were detected during emotion recognition from faces (Golde et al., 2020; Ives-Deliperi & Jokeit, 2019). Another study reported connectivity between occipital, central and parietal regions when participants imitated one another (Dumas et al., 2010). An fMRI study (Parhizi et al., 2018), which employed a visual attention task consisting of detecting direction of movement in the presented stimulus, found significant effects on the connectivity between the occipital cortex and frontal, parietal, temporal regions; similar to this study. Therefore, the findings in this study regarding the occipital cortex might be explained by the social nature of the experiment and the attention of participants on the visual stimuli.

5.2.The Effect of Social Presence

The differences between alone and social conditions in behavioral, physiological and neural measures were:

- In line with the findings in the literature (X. Cui et al., 2012), correlation was detected between social condition and difference of oxygenation changes in several brain regions with fNIRS (Dommer et al., 2012), more prominently in the right PFC (Newman-Norlund, Noordzij, et al., 2007).

- Participants gave more wrong responses and had lower d prime scores in 0-back during the individual condition compared to the social condition.

- Across n-back levels, average heart rates of participants were higher in the individual condition in comparison to the social condition. A higher heart rate is regarded as a sign of higher mental workload (Wilson, 2002).

- Other behavioral and ECG measures (reaction time, missed trials, heart rate variability, autonomic balance) did not show any effect of social task setting.

- Only at the 3-back level blink rate was higher during social setting than individual action. A previous study which also featured the n-back task found a similar relationship between blink rate and higher cognitive load (Ren et al., 2019).

- The intrabrain connectivity analysis of EEG data showed an increase in connectivity between frontal and central electrodes, and decrease between these electrodes and rest of the cortex, across all frequency bands. The literature suggests this frontal increase as a sign of inhibition or top-down control in the social setting (Benedek et al., 2011; Klimesch et al., 2007).

- A significant difference between social and individual task settings was found in N200 on F8, and N200 and N400 on T8 during missed trials, most likely showing uncertainty in response selection (Dimsdale-Zucker et al., 2022).

In general, the effects of social condition were smaller than the effects of the n-back level. Still, it is important to note that the fNIRS analysis showed that changes in oxygenation levels were lower in social condition than individual condition, indicating that participants had lower mental workload during the dual task. EEG and heart rate findings corroborated this result, as well as task accuracy on the 0-back level. This is in contrast to what would be expected according to task co-representation hypothesis (Sebanz et al., 2006). This finding could be explained by social facilitation (Guerin, 2010), the effect that people perform better in easy task in the presence of others, or social loafing (Payne, 2020), which is the effect of people showing less effort during social condition in comparison to when they are alone, also dubbed the Ringelmann effect.

Many participants verbally reported that they have tracked the other participant's performance during the social condition. However, they also stated after the experiments that as the task becomes harder in 2- and 3- back, they stopped tracking the other participant's performance in order to focus on their own task. One of the reasons for this outcome might be that Go trials were separate for the participants, so tracking the other participant during his/her Go trial may not have affected the response during the participant's own Go trial. Another possible reason is that tracking the other participant on these n-back levels may not add much onto the cognitive workload to affect performance significantly, even if the task is co-represented. On the other hand, a recent review on joint action reported that the existence of the context of a joint action is enough by itself to cause cortical activity similar to observing a co-actor (Bolt & Loehr, 2021). It is also possible that social facilitation (Guerin, 2010) or social loafing (Payne, 2020) effect on the social condition balanced the effect of task co-representation.

In the intrabrain connectivity analysis in this study, when own-go and other-go trials were compared in the social task setting, there were a small number of significant differences; on the other hand, when individual and social task settings were compared, numerous significant differences were detected across the cortex in every frequency band.

Finally, it is important to note that neural measures, both fNIRS and EEG, including hyperscanning, were more sensitive to the social nature of the task setting in comparison to ECG, EOG, and behavioral measures, since the latter revealed only minor effects whereas the neural measures indicated several differences.

5.3. The Effect of Extraversion

Significant results regarding extraversion were smaller than other comparisons. It is important to note that the unlike the n-back level and social condition, which were within subject variables, the extraversion score divided the participants into two groups and therefore it was a between subjects variable. Moreover, the number of participants in each group were not equal, which decreases the reliability of the findings.

- Oxy-hemoglobin change was significantly different between extravert and introvert group of participants in 4 out of 16 optodes. Interestingly, it indicated that the extravert group felt higher mental workload. This can stem from the differences between the participants in two different groups, as it seems that the participants in the extravert group found the task to be more difficult in general.

- The analysis of personality traits also did not produce any significant p-values in EEG power when data from extraverts and introverts were compared to each other.

Still, the results of power spectrum analysis only produced significant results when data was analyzed for only extravert participants, and there were no significant effects at all when data from introvert participants was analyzed. From another perspective, if social task setting data and individual task setting data were analyzed separately, it seemed that the EEG powers were reversed between extravert and introvert participants. The EEG literature features similar findings for extraversion in resting state EEG (Baumgartl et al., 2020; Rahmanian et al., 2020; Wacker & Gatt, 2010).

- A small effect was seen as blink rate variability was lower in extravert participants in comparison to introvert participants during the social 2-back task, which would suggest a higher cognitive load in extraverts(Ren et al., 2019), in line with the findings in fNIRS.

- The negative component around P7 around 350 ms was significantly different in correct go trials when introverts and extraverts were compared, which is associated with response selection (Dimsdale-Zucker et al., 2022).

- Significant differences on P300 were found on P8 and F8 electrodes if data from extraverts and introverts were compared for the Go trials during the 3-back level, and on P7 for only extraverts when the participants responded to the No-Go trials during the social session in contrast to the individual session. P300 is associated with mental workload in the literature (Brouwer et al., 2012; Gajewski & Falkenstein, 2014).

- No effect of extraversion was detected in behavioral and ECG measures.

When extraversion values are taken into consideration during hyperscanning analyses, there seems to be a small difference regarding topography plots; however, statistical analyses do not show a strong difference between introvert-introvert and extravert-extravert groups. It is important to note that group sizes are not equal and introvert-introvert group is quite small ($N = 2$).

5.4. General Discussion

Overall, the findings of this study added to the growing knowledge regarding the effect of social presence during a social version of the n-back task with regards to the participant’s personality trait of extraversion, in behavioral measures and modalities of fNIRS, EEG, ECG, EOG and hyperscanning analyses.

Hyperscanning and combining fNIRS and EEG devices provided several benefits to this study: (i) The individual analysis of oxygenation change in fNIRS showed unidirectional effect for the n-back level, whereas WTC analysis on fNIRS data showed that coherence change was different between earlier n-back levels and 3-back, which would be missed if hyperscanning was not conducted. (ii) The individual EEG analyses of power spectrum and ERP only resulted in small effects, on the other hand, EEG-hyperscanning revealed that interbrain connectivity changed with n-back level, and this change was in different directions for different frequency bands, which could have been overlooked without hyperscanning. (iii) Using fNIRS and EEG together provided detailed spatial information about the activation in the prefrontal cortex while still evaluating the changes in other areas across the scalp. Moreover, this study showed that these two devices can be used together without disrupting each other, and future studies may benefit from this combination as well. If this was an only-fNIRS study we would not be able to investigate the difference between own and other's go trials since fNIRS does not provide enough temporal resolution and we could not evaluate the effect seen in different frequency bands, and if this was an only-EEG study, we would have lower resolution in spatial information.

CHAPTER 6

CONCLUSION

As social beings, humans frequently perform tasks not alone but with another person or as part of a large group, forming a social unit (Marsh et al., 2009). Therefore, studying only individual action would not be enough to understand human cognition in its entirety (Hasson et al., 2012; Obhi & Sebanz, 2011). The literature features many studies regarding individual action, although interest is being raised by scholars in the field regarding the need to take a social perspective on cognitive activities (Constantini & Sinigaglia, 2011).

For joint action, it is necessary that agents be able to co-represent the actions, goals and intentions of other agents as well as their own (Pacherie, 2011). This task co-representation would increase mental workload, and might activate brain regions that are silent during individual action, although some scholars argue that there is no task co-representation (Dolk et al., 2013). This discussion is still open and needs further empirical studies, and this work provided new and valuable information. Reaching behavioral synchrony is important for accomplishing a common goal (Hari et al., 2013) and this synchrony can be detected by neuroimaging (Pérez et al., 2017) and physiological measurements (Cornejo et al., 2017).

Improving our understanding of the nature of social interactions and how to measure neural activation and synchronization during these actions via the application of hyperscanning methods, opens the possibility to apply this information for the potential diagnosis and evaluation of success in treatment for medical conditions that cause or be caused by impairments in social skills, such as autism spectrum disorder, schizophrenia, borderline personality disorder and depression (Babiloni & Astolfi, 2014; King-Casas et al., 2005). For example, impairment of forming a link between people as they interact is regarded as a possible cause for autism spectrum disorder, which is linked to deficits in the mirror neuron system and joint action abilities (Rizzolatti & Sinigaglia, 2010).

In addition, by contrasting the findings of these patients with data from healthy participants, the nature of these pathologies can be understood better. A 2017 study showed that children whose motor regions are more active during action observation can cooperate with peers better, and since autism is a disorder regarding impaired social skills, similar neural mechanisms might be involved (Endedijk et al., 2017). Other studies showed that differences in cortical activation, in STS and IPL during games (Su et al., 2022) or parietal regions in the right hemisphere during eye contact (Hirsch et al., 2022) can be used for diagnosis of autism spectrum disorder. Similar associations for neural deficits and disorders include detection of increased resting state functional connectivity between ventral and dorsal subregions of AIC and left inferior frontal gyrus in schizophrenia and bipolar disorder which showed different patterns for each disorder (J. Li et al., 2018).Another work revealed that attention deficit and hyperactivity disorder is linked with reduced volume of ACC and AIC (Lopez-Larson et al., 2012). In the literature, there are examples of how data from healthy participants can be used to help patients (Keysers & Gazzola, 2014) and also how data from patients can help us understand healthy brains (Hutchison et al., 1999). Furthermore, enlightening the nature of social interactions between humans provides valuable information for developing robots that fare better in human robot interaction (Hari et al., 2015), such as robots that aid in the behavioral therapy of children with autism spectrum disorder (Scassellati et al., 2012).

To sum up, this study has been one of the first studies to bring together fNIRS-hyperscanning and EEG-hyperscanning in order to assess the current models about the effect of task sharing and social presence on mental workload with regards to personality traits of participants. Additionally, the neural correlates of working memory load, presence of another person during a task, and the effect of their personality traits were investigated. The findings generally indicated that there was a positive correlation between n-back level and reaction times, task accuracy, heart rate, and oxygenation change across PFC; whereas heart rate variability decreased with n-back level. The effect of social presence was in general smaller than the effect of task difficulty, and hinted towards a lower mental workload during the social task condition in line with the social facilitation model, which could be due to the experiment cohort consisting of more extravert participants than introverts, as there were small differences between measures of extravert and introvert participants. The interbrain connectivity of participants changed with the task difficulty. The intrabrain connectivity analysis showed a larger difference between the individual and social sessions in comparison to own versus the other’s go trials in the social session. Overall, this study measured EEG and fNIRS-hyperscanning during a social n-back task and this provided information regarding the neural mechanism that make it possible for humans to successfully collaborate on a time-constrained and complex task, which is a common and foundational part of social interaction. Understanding the underlying neural mechanism better may lead to the development of new cognitive models or improve the existing ones (Pesquita et al., 2018; Pickering & Garrod, 2013; Vesper et al., 2010; Wolpert et al., 2003).

The main limitations of this study were the low number of introvert participants, and more importantly dyads that consist of both introvert participants. In this study, participants were not pre-selected for any trait, and personality questionnaires were conducted after the experiment; which resulted in a cohort where extraverts are in the majority, and several dyads with one extravert participant and introvert participant. The reason for not eliminating any participants based on personality traits (such as rejecting extravert participants), or specifically matching certain participants together, was to avoid any intervention on the outcome of this explorative study. However, future studies on extraversion or any other personality trait might benefit from a more interventionist approach, such as conducting the questionnaire before recruiting participants for the study, ensuring a balanced distribution of the personality traits in the experiment group, and matching participants into dyads as required for the purpose of the study.

Another limitation of this study was the lack of post-experiment questionnaires. For future studies, it is suggested to obtain written feedback from participants regarding their familiarity with the other participant, how close they felt to the other participant during the experiment, whether they tracked the other participant's performance, and whether they approached the social version of the task as a cooperation or a competition.

In essence, a brief summary of this dissertation is that the effect of n-back level on mental workload is greater than the effect of social presence, and interbrain coherence between participants in the social setting changes with the n-back level.

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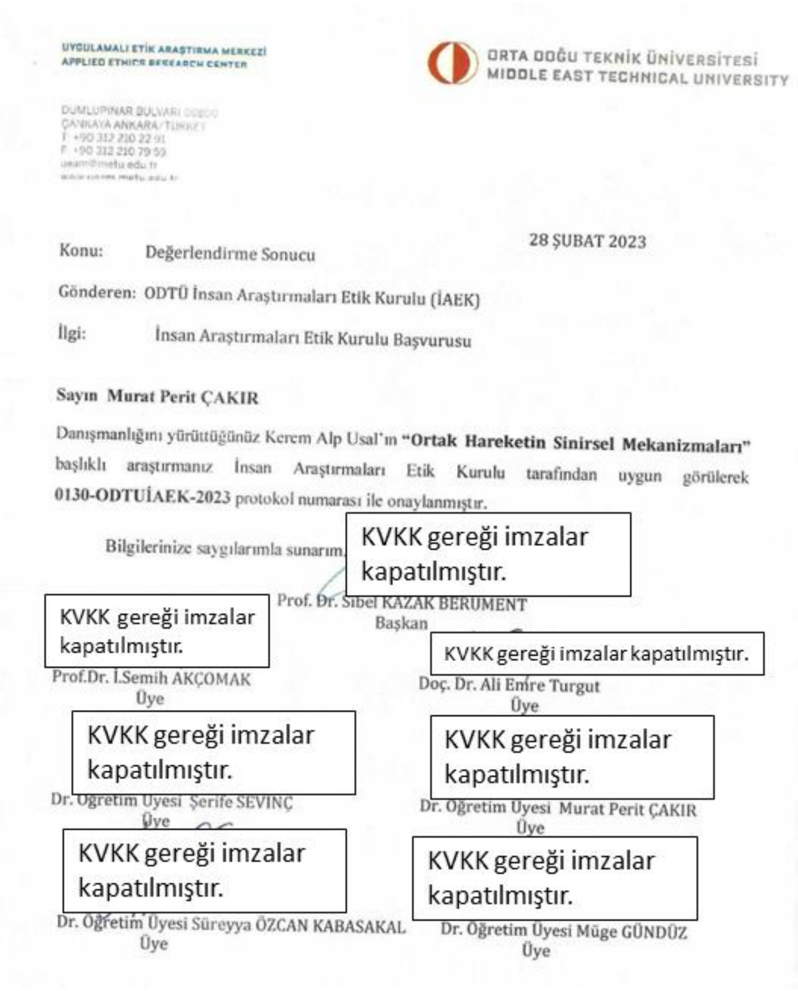
APPENDICES

APPENDIX A

METU ETHICS COMMITTEE APPROVAL



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28 ŞUBAT 2023

Konu: Değerlendirme Sonucu

Gönderen: ODTÜ İnsan Araştırmaları Etik Kurulu (İAEK)

İlgi: İnsan Araştırmaları Etik Kurulu Başvurusu

Sayın Murat Perit ÇAKIR

Danışmanlığını yürüttüğünüz Kerem Alp Usal'ın **"Ortak Hareketin Sinirsel Mekanizmaları"** başlıklı araştırmanız İnsan Araştırmaları Etik Kurulu tarafından uygun görülerek **0130-ODTUİAEK-2023** protokol numarası ile onaylanmıştır.

Bilgilerinize saygılarımla sunarım.

KVKK gereği imzalar kapatılmıştır.

Prof. Dr. Sibel KAZAK BERUMENT
Başkan

KVKK gereği imzalar kapatılmıştır.

Prof.Dr. İ.Semih AKÇOMAK
Üye

KVKK gereği imzalar kapatılmıştır.

Doç. Dr. Ali Emre Turgut
Üye

KVKK gereği imzalar kapatılmıştır.

Dr. Öğretim Üyesi Şerife SEVİNÇ
Üye

KVKK gereği imzalar kapatılmıştır.

Dr. Öğretim Üyesi Murat Perit ÇAKIR
Üye

KVKK gereği imzalar kapatılmıştır.

Dr. Öğretim Üyesi Süreyya ÖZCAN KABASAKAL
Üye

KVKK gereği imzalar kapatılmıştır.

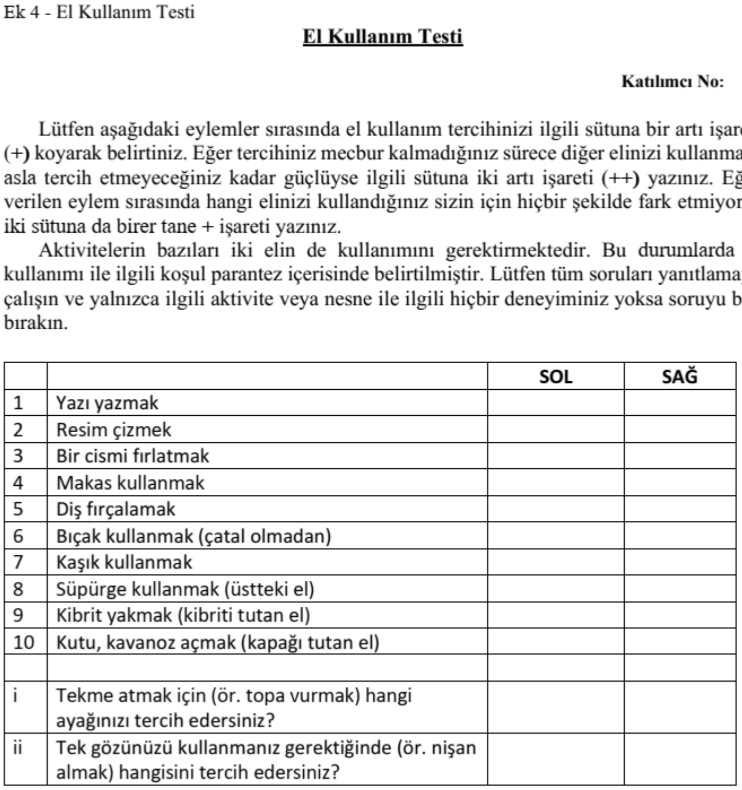
Dr. Öğretim Üyesi Müge GÜNDÜZ
Üye

Figure 120: METU Ethics Committee Approval.

APPENDIX B

FORMS and QUESTIONNAIRES

B.1. Turkish version of Edinburgh Inventory of Handedness (Oldfield, 1971).



Ek 4 - El Kullanım Testi

El Kullanım Testi

Katılımcı No:

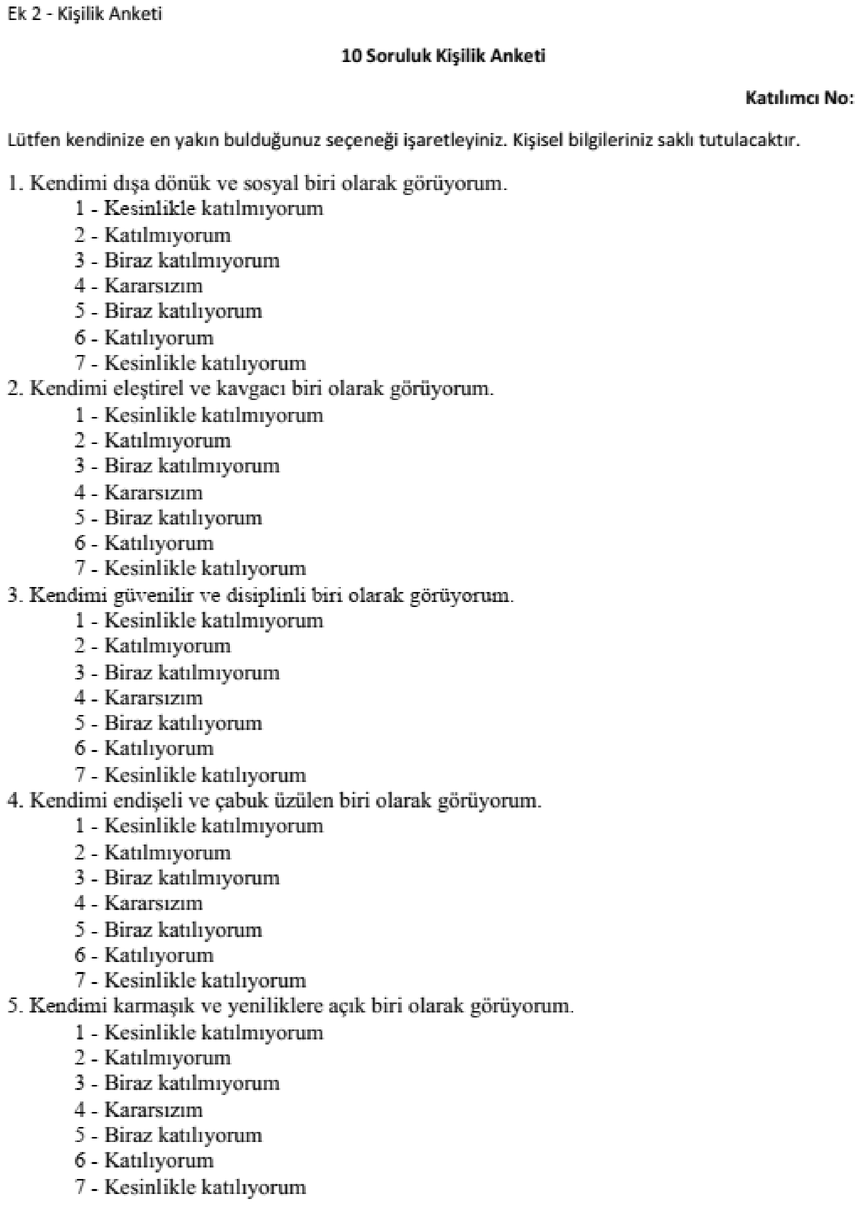
Lütfen aşağıdaki eylemler sırasında el kullanım tercihinizi ilgili sütuna bir artı işareti (**+**) koyarak belirtiniz. Eğer tercihiniz mecbur kalmadığınız sürece diğer elinizi kullanmayı asla tercih etmeyeceğiniz kadar güçlüyse ilgili sütuna iki artı işareti (**++**) yazınız. Eğer verilen eylem sırasında 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 121: Turkish version of Edinburgh Inventory of Handedness (Oldfield, 1971).

B.2. Turkish version of Ten Item Personality Inventory.



Ek 2 - Kişilik Anketi

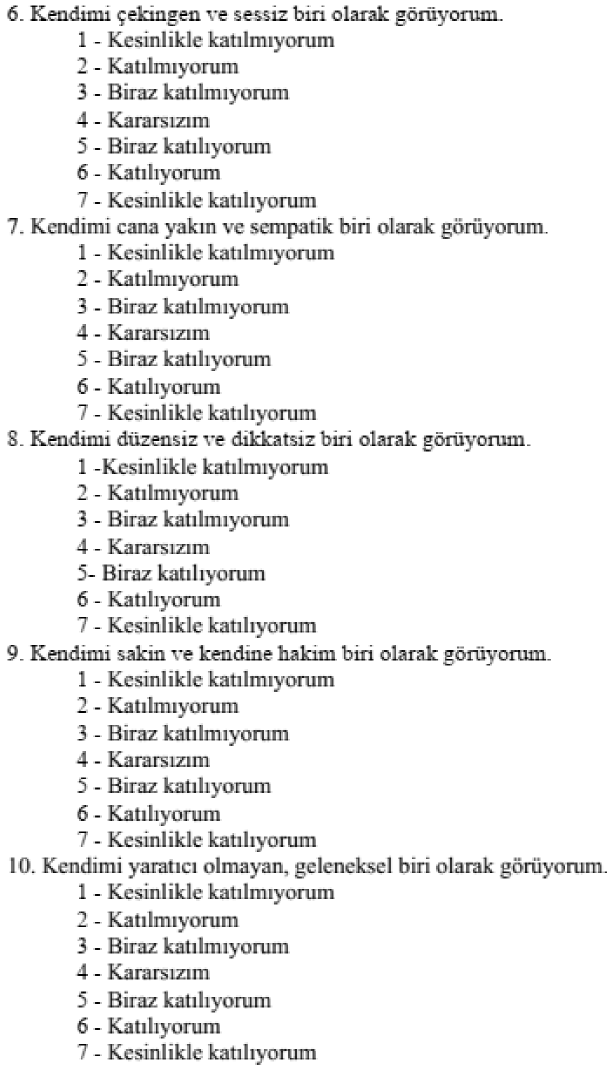
10 Soruluk Kişilik Anketi

Katılımcı No:

Lütfen kendinize en yakın bulduğunuz seçeneği işaretleyiniz. Kişisel bilgileriniz saklı tutulacaktır.

1. Kendimi dışa dönük ve sosyal biri olarak görüyorum.
    - 1 - Kesinlikle katılmıyorum
    - 2 - Katılmıyorum
    - 3 - Biraz katılmıyorum
    - 4 - Kararsızım
    - 5 - Biraz katılıyorum
    - 6 - Katılıyorum
    - 7 - Kesinlikle katılıyorum
2. Kendimi eleştirel ve kavgacı biri olarak görüyorum.
    - 1 - Kesinlikle katılmıyorum
    - 2 - Katılmıyorum
    - 3 - Biraz katılmıyorum
    - 4 - Kararsızım
    - 5 - Biraz katılıyorum
    - 6 - Katılıyorum
    - 7 - Kesinlikle katılıyorum
3. Kendimi güvenilir ve disiplinli biri olarak görüyorum.
    - 1 - Kesinlikle katılmıyorum
    - 2 - Katılmıyorum
    - 3 - Biraz katılmıyorum
    - 4 - Kararsızım
    - 5 - Biraz katılıyorum
    - 6 - Katılıyorum
    - 7 - Kesinlikle katılıyorum
4. Kendimi endişeli ve çabuk üzülen biri olarak görüyorum.
    - 1 - Kesinlikle katılmıyorum
    - 2 - Katılmıyorum
    - 3 - Biraz katılmıyorum
    - 4 - Kararsızım
    - 5 - Biraz katılıyorum
    - 6 - Katılıyorum
    - 7 - Kesinlikle katılıyorum
5. Kendimi karmaşık ve yeniliklere açık biri olarak görüyorum.
    - 1 - Kesinlikle katılmıyorum
    - 2 - Katılmıyorum
    - 3 - Biraz katılmıyorum
    - 4 - Kararsızım
    - 5 - Biraz katılıyorum
    - 6 - Katılıyorum
    - 7 - Kesinlikle katılıyorum

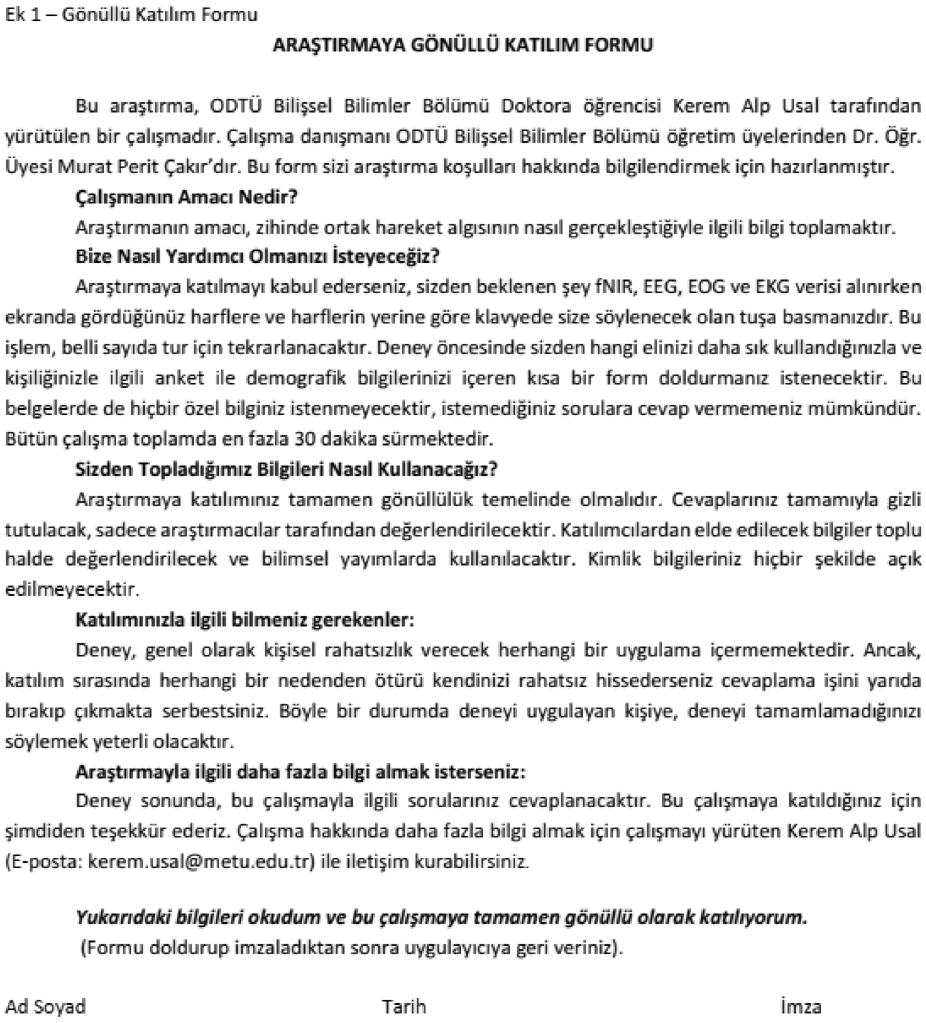
Figure 122: First page of Turkish version of Ten Item Personality Inventory.



6. Kendimi çekingen ve sessiz biri olarak görüyorum.
    - 1 - Kesinlikle katılmıyorum
    - 2 - Katılmıyorum
    - 3 - Biraz katılmıyorum
    - 4 - Kararsızım
    - 5 - Biraz katılıyorum
    - 6 - Katılıyorum
    - 7 - Kesinlikle katılıyorum
7. Kendimi cana yakın ve sempatik biri olarak görüyorum.
    - 1 - Kesinlikle katılmıyorum
    - 2 - Katılmıyorum
    - 3 - Biraz katılmıyorum
    - 4 - Kararsızım
    - 5 - Biraz katılıyorum
    - 6 - Katılıyorum
    - 7 - Kesinlikle katılıyorum
8. Kendimi düzensiz ve dikkatsiz biri olarak görüyorum.
    - 1 -Kesinlikle katılmıyorum
    - 2 - Katılmıyorum
    - 3 - Biraz katılmıyorum
    - 4 - Kararsızım
    - 5- Biraz katılıyorum
    - 6 - Katılıyorum
    - 7 - Kesinlikle katılıyorum
9. Kendimi sakin ve kendine hakim biri olarak görüyorum.
    - 1 - Kesinlikle katılmıyorum
    - 2 - Katılmıyorum
    - 3 - Biraz katılmıyorum
    - 4 - Kararsızım
    - 5 - Biraz katılıyorum
    - 6 - Katılıyorum
    - 7 - Kesinlikle katılıyorum
10. Kendimi yaratıcı olmayan, geleneksel biri olarak görüyorum.
    - 1 - Kesinlikle katılmıyorum
    - 2 - Katılmıyorum
    - 3 - Biraz katılmıyorum
    - 4 - Kararsızım
    - 5 - Biraz katılıyorum
    - 6 - Katılıyorum
    - 7 - Kesinlikle katılıyorum

Figure 123: Second page of Turkish version of Ten Item Personality Inventory.

B.3. Form of Voluntary Participation in Experiment.



Ek 1 – Gönüllü Katılım Formu

ARAŞTIRMAYA GÖNÜLLÜ KATILIM FORMU

Bu araştırma, ODTÜ Bilişsel Bilimler Bölümü Doktora öğrencisi Kerem Alp Usal tarafından yürütülen bir çalışmadır. Çalışma danışmanı ODTÜ Bilişsel Bilimler Bölümü öğretim üyelerinden Dr. Öğr. Üyesi Murat Perit Çakır'dır. Bu form sizi araştırma koşulları hakkında bilgilendirmek için hazırlanmıştır.

Çalışmanın Amacı Nedir?

Araştırmanın amacı, zihinde ortak hareket algısının nasıl gerçekleştiğiyle ilgili bilgi toplamaktır.

Bize Nasıl Yardımcı Olmanızı İsteyeceğiz?

Araştırmaya katılmayı kabul ederseniz, sizden beklenen şey fNIR, EEG, EOG ve EKG verisi alınırken ekranda gördüğünüz harflere ve harflerin yerine göre klavyede size söylenecek olan tuşa basmanızdır. Bu işlem, belli sayıda tur için tekrarlanacaktır. Deney öncesinde sizden hangi elinizi daha sık kullandığınızla ve kişiliğinizle ilgili anket ile demografik bilgilerinizi içeren kısa bir form doldurmanız istenecektir. Bu belgelerde de hiçbir özel bilginiz istenmeyecektir, istemediğiniz sorulara cevap vermemeniz mümkündür. Bütün çalışma toplamda en fazla 30 dakika sürmektedir.

Sizden Topladığımız Bilgileri Nasıl Kullanacağız?

Araştırmaya katılımınız tamamen gönüllülük temelinde olmalıdır. Cevaplarınız tamamıyla gizli tutulacak, sadece araştırmacılar tarafından değerlendirilecektir. Katılımcılardan elde edilecek bilgiler toplu halde değerlendirilecek ve bilimsel yayımlarda kullanılacaktır. Kimlik bilgileriniz hiçbir şekilde açık edilmeyecektir.

Katılımınızla ilgili bilmeniz gerekenler:

Deney, genel olarak kişisel rahatsızlık verecek herhangi bir uygulama içermemektedir. Ancak, katılım sırasında herhangi bir nedenden ötürü kendinizi rahatsız hissederseniz cevaplama işini yarıda bırakıp çıkmakta serbestsiniz. Böyle bir durumda deneyi uygulayan kişiye, deneyi tamamlamadığınızı söylemek yeterli olacaktır.

Araştırmayla ilgili daha fazla bilgi almak isterseniz:

Deney sonunda, bu çalışmayla ilgili sorularınız cevaplanacaktır. Bu çalışmaya katıldığınız için şimdiden teşekkür ederiz. Çalışma hakkında daha fazla bilgi almak için çalışmayı yürüten Kerem Alp Usal (E-posta: kerem.usal@metu.edu.tr) ile iletişim kurabilirsiniz.

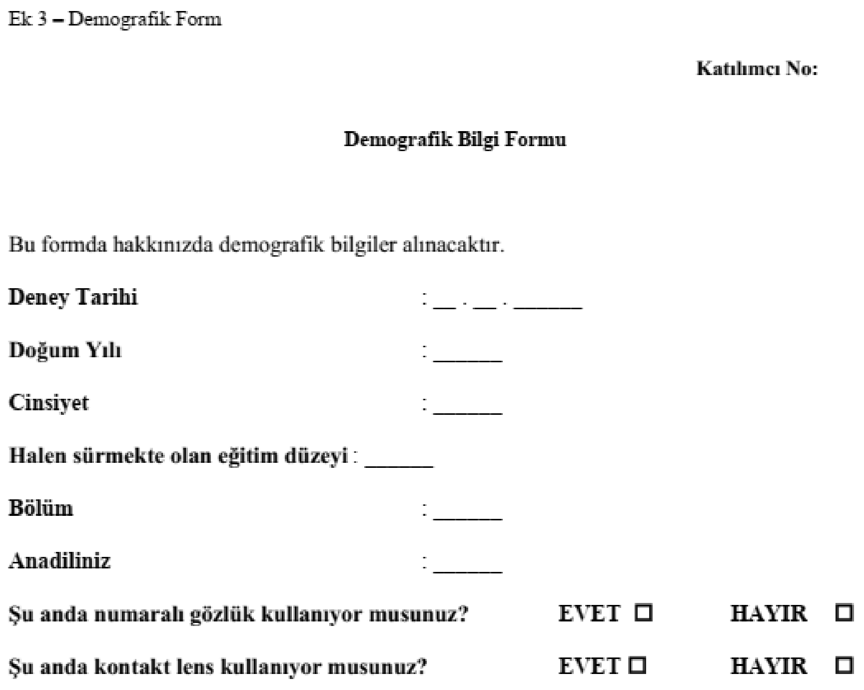
Yukarıdaki bilgileri okudum ve bu çalışmaya tamamen gönüllü olarak katılıyorum.

(Formu doldurup imzaladıktan sonra uygulayıcıya geri veriniz).

Ad Soyad	Tarih	İmza

Figure 124: Form of Voluntary Participation in Experiment.

B.4. Demographic Information Form.



Ek 3 – Demografik Form

Katılımcı No:

Demografik Bilgi Formu

Bu formda hakkınızda demografik bilgiler alınacaktır.

Deney Tarihi : __ . __ . ______

Doğum Yılı : ______

Cinsiyet : ______

Halen sürmekte olan eğitim düzeyi : ______

Bölüm : ______

Anadiliniz : ______

Şu anda numaralı gözlük kullanıyor musunuz? **EVET** ☐ **HAYIR** ☐

Şu anda kontakt lens kullanıyor musunuz? **EVET** ☐ **HAYIR** ☐

Figure 125: Demographic Information Form.

CURRICULUM VITAE

PERSONAL INFORMATION

Surname, Name: Usal, Kerem Alp

Nationality: Turkish

Marital Status: Married

EDUCATION

Degree	Institution	Year of Graduation
MS	METU, Graduate School of Informatics, Department of Cognitive Science	2016
BS	Hacettepe University, Faculty of Medicine	2012
High School	Ankara Science High School	2006

WORK EXPERIENCE

Year	Place	Role
2019-Present	METU, Graduate School of Informatics, Department of Cognitive Science	Teaching Assistant
2016-2018	İleri Biyotek Co. Ltd.	Researcher

FOREIGN LANGUAGES

Native Turkish, Advanced English.

PUBLICATIONS

ORCID: 0000-0002-7079-4008

Scopus ID: 57224528832

Kuperman, V., Siegelman, N., Schroeder, S., Acartürk, C., Alexeeva, S., Amenta, S., Bertram, R., Bonandrini, R., Brysbaert, M., Chernova, D., Fonseca, S. M. D., Dirix, N., Duyck, W., Fella, A., Frost, R., Gattei, C. A., Kalaitzi, A., Kwon, N., Lõo, K., Marelli, M., Papadopoulos, T. C., Protopapas, A., Savo, S., Shalom, D. E., Slioussar, N., Stein, R., Sui, L., Taboh, A., Tønnesen, V., & Usal, K. (2022). Text reading in English as a second language: Evidence from the Multilingual Eye-Movements Corpus. Studies in Second Language Acquisition, 1-35. doi:10.1017/S0272263121000954

Siegelman, N., Schroeder, S., Acartürk, C., Ahn, H. D., Alexeeva, S., Amenta, S., Bertram, R., Bonandrini, R., Brysbaert, M., Chernova, D., Fonseca, S. M. D., Dirix, N., Duyck, W., Fella, A., Frost, R., Gattei, C. A., Kalaitzi, A., Kwon, N., Lõo, K., Marelli, M., Papadopoulos, T. C., Protopapas, A., Savo, S., Shalom, D. E., Slioussar, N., Stein, R., Sui, L., Taboh, A., Tønnesen, V., Usal, K., & Kuperman, V. (2022). Expanding horizons of cross-linguistic research on reading: The Multilingual Eye-movement Corpus (MECO). Behavior Research Methods, 1-21. https://doi.org/10.3758/s13428-021-01772-6

Acarturk, C., Indurkya, B., Nawrocki, P., Sniezynski, B., Jarosz, M. & Usal, K. A. (2021). Gaze aversion in conversational settings: An investigation based on mock job interview. Journal of Eye Movement Research, 14(1):1. Digital Object Identifier: 10.16910/jemr.14.1.1 ISSN: 1995-8692.

Usal, K. A., & Çakır, M. P. (2020). Neurophysiological investigation of dual N-back task with fNIRS and EEG hyperscanning. Anatomy: International Journal of Experimental & Clinical Anatomy, 14.

Usal, K. A. (2016). Effects of joint action and nature of task setting on time perception (Master's thesis, Graduate School of Informatics, METU).

PATENTS

2018 – Present: Hızlı Yara İyileştirici Hidrojel (Quick Wound Healing Microgel) - No: TR 2015 – co-owner with Tuğba Dursun 15159 B

CONTRIBUTED PROJECTS

2022-2023 Pilot Health Monitoring (PHM) Project – with Dr. Murat Perit Çakır, Dr. Barbaros Yet, METU

2019-2022 GENIUS Project (Bilişsel İş Yükünün Ölçülerek Uçuş Simülatör Eğitimlerinin Kişiselleştirilmesi (GENIUS) Projesi) – with Dr. Murat Perit Çakır, Dr. Cengiz Acartürk, Dr. Özden Özcan Top, METU

2019-2022 Multilingual Eye-movement Corpus (MECO) – with Dr. Cengiz Acartürk, METU; Dr. Victor Kuperman & Dr. Noam Siegelman, McMaster University, Canada

2018-2019 TÜBİTAK 1001 project 117E021 - A gaze-mediated framework for multimodal Human Robot Interaction – with Dr. Cengiz Acartürk, METU

2017-2018 BAP-07-04-2017-003 "The effect of social setting on cognitive performance and time perception" funded by Informatics Institute, METU – with Dr. Annette Hohenberger, METU

2016-2018 TÜBİTAK 1512 project – Fast Healing Microgel – Project No: 2150169 – Project co-manager with Dr. Tuğba Dursun

PRESENTATIONS

2021 Oral Presentation at 19th National Neuroscience Congress (in Turkish, 19. Ulusal Sinirbilim Kongresi), 21-23 November 2021, Bilkent Üniversitesi, Ankara, Turkey. Online.

2016 Oral Presentation at ESPP 2016, 24th Annual Meeting of the European Society for Philosophy and Psychology, August 10-13, St Andrews, Scotland

2015 Oral Presentation at II. Career Development Days at Cukurova University, Adana, Turkey

2015 Oral Presentation at METU New Ideas New Businesses Competition, METU, Ankara, Turkey

2015 Oral Presentation at 17th European Conference on Developmental Psychology, September 8-12th, Braga, Portugal.

2015 Panel speaker at Hacettepe University Mehmet Akif Book Club, Ankara, Turkey

2015 Oral presentation at Alternative Career Days in Ankara Science High School, Ankara, Turkey

2009 Oral presentation at 5th Human Sciences in Medicine Congress. May 13th, Ankara, Turkey.

ORGANIZED SCIENTIFIC EVENTS

2018 HRI@METU: Symposium on Human Robot Interaction, 13 December 2018, METU, Ankara, Turkey – with Dr. Cengiz Acartürk, METU.

ACCOMPLISHMENTS and AWARDS

2018 157th in National Graduate School Entrance Exam (ALES, with a score of 95.28/100, among 272865 applicants)

2018 Received Poster Award in the 2nd Open Research Day, 24 May 2018, METU, Ankara, Turkey. - "Worthy of Mention" - K. A. Usal, E. Yılmaz, D. Zeyrek. Differences In Inter-Annotator Agreement Between Translated and Original Language TED talks.

2017 Received funds for and Project coordinator in Institute funded scientific research project (BAP) on the effect of social setting on cognitive performance and time perception, Informatics Institute, METU

2016 Received TÜBİTAK 1512 Entrepreneurship Support Program (out of 3200 participants)

2015 Received Travel Grant from Jacobs Foundation for 17th European Conference on Developmental Psychology, September 8-12th, Braga, Portugal.

2015 Finalist in METU New Ideas New Businesses Competition (out of 6800 participants)

2013 68th in National Graduate School Entrance Exam (ALES, with a score of 94/100, among 223442 applicants)

2007 Received 2nd place award at Poster Competition in 3rd Human Sciences in Medicine Congress. April 6th, Ankara, Turkey.

2006 366th (quantitative) in the National University Entrance Exam (among 1,5 million competitors)

CONFERENCE ABSTRACTS

K. A. Usal & M. P. Çakır. (2023) Wavelet Transform Coherence on fNIRS-hypercanning data from Cooperative n-Back task. The 9th International Symposium on Brain and Cognitive Science (ISBCS 2023), 7 May 2023, Özyeğin University, Istanbul, Turkey. (Poster Presentation)

K. A. Usal & M. P. Çakır. (2022) Cooperative Dual N-Back Task: Effect of Personality. The 8th International Symposium on Brain and Cognitive Science (ISBCS 2022), 29 May 2022, Koç University, Istanbul, Turkey. (Online Poster Presentation)

K. A. Usal & M. P. Çakır. (2021) Ortak Hareket Sırasında EEG ve fNIRS Ölçümlerine Kişiliğin Etkisi (Effect of Personality on EEG and fNIRS Measurements During Joint Action). 19. Ulusal Sinirbilim Kongresi (19th National Neuroscience Congress), 21-23 November 2021, Bilkent Üniversitesi, Ankara, Turkey. (Online Oral Presentation, in Turkish)

K. A. Usal & M. P. Çakır. (2020) İkili N-Geri Görevinin fNIRS ve EEG Hipertarama ile Nörofizyolojik İncelemesi (Neurophysiological Investigation of Dual N-Back Task with fNIRS and EEG Hyperscanning). 18. Ulusal Sinirbilim Kongresi (18th National Neuroscience Congress), 6-9 November 2020, Bilkent Üniversitesi, Ankara, Turkey. (Online Poster Presentation, in Turkish)

K. A. Usal, E. Yılmaz, D. Zeyrek. (2018) Differences In Inter-Annotator Agreement Between Translated and Original Language TED talks. The 2nd Open Research Day, 24 May 2018, METU, Ankara, Turkey. (Poster Presentation)

K. A. Usal, F. A. Demiroz, E. Pourreza, M. Hassanpour, A. Hohenberger, M. P. Cakir. (2018) Eye Movement Analysis in the Simon Task. The 2nd Open Research Day, 24 May 2018, METU, Ankara, Turkey. (Poster Presentation)

K. A. Usal, A. Hohenberger. (2018) Changes in Time Perception for Joint Action and Social Facilitation. The 2nd Open Research Day, 24 May 2018, METU, Ankara, Turkey. (Poster Presentation)

K. A. Usal, F. A. Demiroz, E. Pourreza, M. Hassanpour, A. Hohenberger, M. P. Cakir. (2018) Eye Movement Analysis in the Simon Task. Fifth International Symposium on Brain and Cognitive Science (ISBCS 2018), May 6th, Bogazici University, Istanbul, Turkey. (Poster Presentation)

K. A. Usal, A. Hohenberger. (2018) Changes in Time Perception for Joint Action and Social Facilitation. Social Cognition Conference, April 7-8, Bilkent, Ankara, Turkey. (Poster Presentation)

K. A. Usal, A. Hohenberger. (2017) The Effects of Social Task Setting on Time Perception. The 39th Annual Meeting of the Cognitive Science Society (Cog Sci 2017), July 26th – July 29th 2017, London, UK. (Poster Presentation)

B. Erdem, K. A. Usal, A. Hohenberger (2017) Smell Recognition and Odor-Shape Matching. Open Research Day, 24 May 2017, METU, Ankara, Turkey. (Poster Presentation)

B. Serhan, K. A. Usal, A. Hohenberger (2017) Difference between Tactile and Auditory Modalities in Time Perception. Open Research Day, 24 May 2017, METU, Ankara, Turkey. (Poster Presentation)

O. Deniz, K. A. Usal, M. P. Cakir (2017) Connectionist Model for the Simon Task. Open Research Day, 24 May 2017, METU, Ankara, Turkey. (Poster Presentation)

B. Erdem, K. A. Usal, A. Hohenberger (2017) Smell Recognition and Odor-Shape Matching. Fourth International Symposium on Brain and Cognitive Science

(ISBCS 2017), April 30th, Hacettepe University, Ankara, Turkey. (Poster Presentation)

B. Serhan, K. A. Usal, A. Hohenberger (2017) Difference between Tactile and Auditory Modalities in Time Perception. Fourth International Symposium on Brain and Cognitive Science (ISBCS 2017), April 30th, Hacettepe University, Ankara, Turkey. (Poster Presentation)

O. Deniz, K. A. Usal, M. P. Cakir (2017) Connectionist Model for the Simon Task. Fourth International Symposium on Brain and Cognitive Science (ISBCS 2017), April 30th, Hacettepe University, Ankara, Turkey. (Poster Presentation)

K. A. Usal, T. Dursun (2016) A Novel Hydrogel System for the Wound Healing in the Diabetic Patients. 3rd International Congress on Biosensors, 5-7 October 2016, Hacettepe University, Ankara, Turkey. (Poster Presentation)

K. A. Usal, A. Hohenberger (2016) Effects of Social Condition on Prospective Time Estimation. ESPP 2016, 24th Annual Meeting of the European Society for Philosophy and Psychology, August 10-13, St Andrews, Scotland. (Oral Presentation)

K. A. Usal, A. Hohenberger. (2016) The Interaction Between the Social Aspect of Task Setting and Time Perception. Third International Symposium on Brain and Cognitive Science (ISBCS 2016), May 8th, Yeditepe University, Istanbul, Turkey. (Poster Presentation)

K. A. Usal, T. Dursun, A. Hohenberger (2015) Theory of Mind in 4 and 6-year-old Children Studied Through the Shape-Bias. 17th European Conference on Developmental Psychology, September 8-12th, Braga, Portugal. (Oral Presentation)

K. A. Usal, F. Uysal, B. Kahyaoglu, M.P. Cakir (2015) Neural Correlates of Economic Bubble: an fNIR Study. Second International Symposium on Brain and Cognitive Science (ISBCS 2015), April 19th, Ankara, Turkey. (Poster Presentation)

K. A. Usal, T. Dursun, A. Hohenberger (2014) Theory of Mind in 4 and 6-year-old Children Studied Through the Shape-Bias. Cognitive Science Seminars, CogSci in Germany, CogSci in Turkey, May 23rd, Ankara, Turkey. (Poster Presentation)

K. A. Usal, S. Toprakli, B. Tozduman, G. Taş (2009) Which Specialty in Medicine? 5th Human Sciences in Medicine Congress. May 13th, Ankara, Turkey. (Oral Presentation).

K. A. Usal, Y. Eraslan, C. Onal (2008) Unit 731: Science During World War II. 4th Human Sciences in Medicine Congress. May 14th, Ankara, Turkey. (Poster Presentation)

K. A. Usal, I. Yalcınkaya, P. Eryaman, P.B. Dogan (2007) Profile of Medicine and Medical Professionals in Humor Magazines. 3rd Human Sciences in Medicine Congress. April 6th, Ankara, Turkey. (Poster Presentation)

ATTENDED CONFERENCES, WORKSHOPS, SUMMER SCHOOLS

2022 The 3rd Open Research Day, 24 May 2018, METU, Ankara, Turkey.

2021 Bioinfocongress 2021, September 24 – 26, Bioinforange.

2021 Alzheimer’s Association International Conference® 2021 (AAIC®), July 26-30.

2021 BMES T280 132 - Brain|Technology Convergence I: Cyber—Brain Systems, Global Innovation Partnerships, Drexel University School of Biomedical Engineering, Science and Health Systems, Summer 2021. Instructors: Banu Onaral and Lei Wang.

2021 Interactivism in Perspective, 25-27 June, Interactivist Summer Institute 2021.

2021 34. Ulusal Dilbilim Kurultayı, ODTÜ, 29-30 Nisan 2021 (34th National Linguistics Convention, METU, April 29-30, 2021).

2021 g.tec BCI & Neurotechnology Spring School 2021. April 12-21, 2021.

2021 13. Tıp Bilişimi Kongresi (13th Congress of Medical Informatics), March 24-27 2021.

2021 Bioinfoconference 2021, Biyoenformatik ve Disiplinlerarası Yaklaşımlar Konferansı (Bioinformatics and Interdisciplinary Approaches Conference), March 20 – 22, Bioinforange.

2016 UNAM NanoDay 2016, May 26, Bilkent University, Ankara, Turkey

2016 2. METU Science Days, May 14-15, METU, Ankara, Turkey

2014 8. Aykut Kence Evolution Conference, April 26-27, METU, Ankara, Turkey