AN INVESTIGATION OF BRAIN-TO-BRAIN CONNECTIVITY PATTERNS DURING A COOPERATIVE FLUID INTELLIGENCE TASK

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ABSTRACT

AN INVESTIGATION OF BRAIN-TO-BRAIN CONNECTIVITY PATTERNS DURING A COOPERATIVE FLUID INTELLIGENCE TASK

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Several studies have shown that executing the same task simultaneously can create synchronization among participants' brain hemodynamics. In this thesis, we examined multiple participants' brain hemodynamics while they are engaged in cooperative Sandia matrices (free version Raven's matrices) task that requires them to coordinate their gaze position to reach information needed to solve the given puzzle. We used functional near-infrared spectroscopy (fNIRS) hyperscanning to observe the brain hemodynamics of two participants simultaneously while they are engaged in a joint task. We found that, forcing people to cooperate in a fluid intelligence task increases behavioral and neural coherence between them. We found increase activation and coherence in areas close to dorsolateral prefrontal cortex and dorsomedial prefrontal cortex. Furthermore, we found that the difficulty of the joint task enhances the neural coherence between people. These finding implies that jointly solving a problem causes a degree of neural synchrony among people and the degree of synchrony increases with the difficulty of the problem.

Keywords: cooperative problem solving, fNIRS, brain-to-brain coherence, hyperscanning, eye tracking.

ÖZ

ORTAK AKIŞKAN ZEKA GÖREVLERİ SIRASINDAKİ BEYİNLER ARASI BAĞLANTISALLIK ÖRÜNTÜLERİNİN İNCELENMESİ.

TAŞCI, ÇAĞATAY

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Bazı çalışmalar, aynı görevi simültane olarak gerçekleştirmenin katılımcıların beyin hemodinamikleri arasında senkronizasyona yol açtığını göstermiştir.Bu tezde katılımcların sunulan bulmacanın parçalarına ulaşmak için gözbakışlarını ortak bir şekilde kullanmaları gereken Sandia matrisleri (Raven matrislerinin ücretsiz bir versiyonu) görevini gerçekleştirirkenki beyin hemodinamiklerini incelemektir. Katılımcılar simültane bir şekilde yapboz formatında hazırlanmış akışkan zeka görevine angaje olmuşlarken beyin hemodinamikleri NIRS (kızıl-ötesi tayfölçümü) cihazı ile ölçülmüştür. Bu çalışmanın sonucunda dorsolateral prefrontal korteks ve dorsomedial prefrontal korteks bölgelerine yakın beyin bölgelerinde aktivasyon ve bağdaşımlılığa rastlanmıştır. Buna ek olarak, ortak olarak yapılan görevin zorluğunun bu bağdaşıklığı arttırdığı gözlemlenmiştir. Bu bulgular, ortaklaşa problem çözmenin kişiler arasında problemin zorluğuyla beraber artış gösteren bir bağdaşıklığa sebep olduğunu ima etmektedir.

Anahtar Kelimeler: ortaklaşa problem çözme , fNIRS, beyinlerarası bağdaşımlılık, hipertarama, göz izleme.

To my family.

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LIST OF ABBREVIATIONS

dlPFC	Dorsolateral Prefrontal Cortex
dmPFC	Dorsomedial Prefrontal Cortex
EEG	Electro-Encephalography
fMRI	Functional Magnetic Resonance Imaging
fNIRS	Functional Near-Infrared Spectroscopy
IFC	Inferior Frontal Cortex
MBLL	Modified Beer-Lambert Law
PET	Positron Emission Tomography
RAPM	Raven's Advanced Progressive Matrices
RPM	Raven's Progressive Matrices
STS	Superior Temporal Sulcus
vmPFC	Ventromedial Prefrontal Cortex
WTC	Wavelet Transform Coherence
WAIS	Wechsler Adult Intelligence Scale

CHAPTER 1

INTRODUCTION

Humans tend to alter their actions with respect to other humans during social interaction. When they alter their actions to coordinate with each other in order to achieve a common goal, it is called joint action (Sebanz, Bekkering, & Knoblich, 2006). Coordination or synchrony among multiple people can be apparent in tasks such as dancing, singing, marching so forth. In these types of tasks, body movements and utterances can happen in a simultaneous fashion. Yet there are subtler types of coordination among people that can occur in different types of tasks. For example, when people engage in dialogue, their choice of words and use of grammar can be aligned with each other (Garrod & Pickering, 2009). When people get aligned in a dialogue, they do not use the same word simultaneously, but their word choices and grammar use, change with respect to each other so that they are more likely to use the same words and grammatical structures during dialog. This suggests that joint action and coordination is more than coordination of immediate behavior, so agents are coordinated in cycles with various periods. Therefore, it is suggested that agents, who engage in joint action, align their goals, physical movements, and/or representations. As suggested by (Valdesolo, Ouyang, & DeSteno, 2010), when people engage in joint action, this alignment persists after the current joint action is completed, so that it increases the performance during subsequent joint actions, even if the latter action has a different domain than the former.

There is a wide array of studies, which investigates humans' cognitive and behavioral performance during a variety of tasks. Often, these studies observed humans in isolation. However, a task's nature can differ with respect to whether this task is performed in isolation or in a social context. When people engaged in joint action, they do not necessarily divide the labor equally. People's role in a joint task can be the same or complimentary (Sebanz, Knoblich, & Prinz, 2003). Furthermore, jointly performing a task can be less demanding, even if people have more parameters to consider. For example, giving a monologue can be more tedious than engaging in a dialogue, although in dialogue interlocutors have to consider each other and produce responses accordingly (Menenti, Pickering, & Garrod, 2012). Based upon similar examples, there are arguments for the necessity to quantify the neural correlates of joint action in natural, social environments (Montague et al., 2002). Increasing accessibility of neuroimaging devices and developing technologies such as eye tracking and body tracking, allows us to quantitatively investigate both neural and behavioral aspects of joint action, during more ecological social environments.

The term hyperscanning refers to imaging multiple individuals (usually two) simultaneously during the involvement of a joint task (Montague et al., 2002). In recent years, hyperscanning studies have become a powerful technique to investigate joint action. Studies such as Funane et al. (2011), Cui, Bryant, and Reiss (2012) ,Osaka et al. (2015) employed hyperscanning using multiple fNIRS devices to study neural correlates of joint action. Analyses of simultaneously collected neuroimaging data yielded promising results. However, the results of hyperscanning studies showed that hyperscanning is not only useful but also necessary. Findings in studies such as Cui et al. (2012), Dumas, Chavez, Nadel, and Martinerie (2012), Holper, Scholkmann, and Wolf (2012) found evidence of inter-brain relations during joint action. Evidence for inter-brain relations found in these studies emerged from combined analyses of two neuroimaging data. In this study, a hyperscanning setup including dual fNIRS and dual eye tracking systems is employed to investigate neural correlates of a joint activity where two participants attempted fluid intelligence tasks together.

To sum up, the aim of this study is to investigate the neural correlates of joint action. In this study, participants are engaged in a fluid intelligence task, where they are forced to cooperatively use their eye gaze to uncover parts of fluid intelligence puzzle. Sandia matrices (Matzen et al., 2010), computer-generated version of Raven's Progressive Matrices (J. C. Raven, 1941) is used as the fluid intelligence task. Participants are presented with a closed version of these matrices, where they have to fixate on the same part of a 3x3 matrix to uncover the contents of that particular cell. The uncovered part remained open as long as both participants remain fixated on that part. The task of the participants is to uncover all parts of the puzzle while and solve the problem by identifying the best option for completing the pattern while they are engaged in dialogue. During this process participants' prefrontal cortices are monitored simultaneously by using a dual fNIRS setup. As our literature review suggests, this type of experimental paradigm where both hyperscanning and dual eye tracking methods are utilized to investigate joint action during problem-solving has not been employed by any previous study. However, (Jermann et al., 2009) used a similar task to test the predictive power of dual eye tracking and speech data to estimate task performance, without considering an optical brain imaging dimension.

1.1 Research Problem, Question, and Hypotheses

In this study, the research problem is to investigate brain to brain coherence, in the prefrontal cortices of pairs of participants during a joint fluid intelligence task. Experiments consist of two conditions. In the *open* condition, questions were presented to participants without forcing them to cooperate by using eye trackers. In the *closed* conditions, participants were forced to cooperate by using the eye trackers. In both conditions, participants were free to engage in a dialogue.

During the experiments, hemodynamic changes in participants' prefrontal cortices are monitored by using a dual fNIRS setup. Furthermore, eye fixation data is collected by using a dual eye tracking setup. Coherence values in both modalities are calculated by using the Wavelet Transform Coherence (WTC) algorithm.

1.1.1 Research Questions

The research question and hypotheses investigated in this study are as follows:

1. Does forcing people to engage in a joint task by rendering parts of the information in a puzzle individually inaccessible lead to an increased brain-to-brain coherence in the prefrontal cortex?
2. Is the level of brain-to-brain coherence modulated by the difficulty and the type of the joint task?

1.1.2 Hypotheses

Considering the evidence in the literature for increased neural coherence during engagement of joint tasks (Cui et al., 2012; Osaka et al., 2015) we hypothesized that by making a problem-solving task individually inaccessible, we can force the participants by acting jointly, thus we can observe increased neural synchrony (H1). We also hypothesized that, as the task becomes more demanding, we will observe increased coherence as the incentive to cooperate would be increased (H2). Furthermore, we shall note that increasing difficulty means that participants would have to revisit parts of the problem multiple times so that they would have to try to coordinate their behavior multiple times in one question. Therefore, our hypotheses, derived from our research questions are listed as follows:

1. Forcing people to cooperate in problem-solving will lead to increased coherence in their brain hemodynamics.
2. The likelihood of observing increased neural coherence during a joint problem solving will increase as the problem becomes more demanding.

1.2 Scope and Organization of the Thesis

The scope of this thesis is to investigate neural synchrony during joint fluid intelligence task. We devised an experiment in order to force people to cooperate during a fluid intelligence task. As the fluid intelligence task, we selected the free, computer-generated version of Raven's Progressive Matrices, namely the Sandia Matrices. We made this task joint by forcing participants to coordinate their gaze positions by using a gaze contingent displayed based on dual eye trackers. However, we should note that we did not measure fluid intelligence scores, as it lies outside of the scope of our research questions and hypotheses.

In the following chapter (chapter 2), a literature review about the theoretical background of the study is laid out. In this chapter, topics of joint action and fluid intelligence are reviewed with the emphasis of neuroimaging studies in these topics. In chapter 3, the experimental design and data processing is explained. Results of experiments and statistical analyses are reported in chapter 4. In the last chapter, these results are discussed and possible future studies are addressed with respect to limitations.

CHAPTER 2

BACKGROUND

A review of related literature, which constitutes the background of this study, is provided in this chapter. Two main body of research is reviewed. As the study is based on a joint fluid intelligence task, relevant literature on fluid intelligence and joint action are reviewed. Both parts consist of a general review of the topic followed by neural correlates of these topics. In the review of fluid intelligence, literature about the measurement of fluid intelligence, and individual differences are excluded because these topics are beyond the scope of this thesis. The review on joint action is concentrated on neural correlates of joint action, especially on hyperscanning studies.

2.1 Review of Fluid Intelligence

Intelligence is one of the most intriguing topics in the investigation of human mind. Measuring and quantifying the human capacity to tackle problems and devising solutions is a matter of great interest. These abilities are classified according to the type of problem and required abilities to solve it. Cattell (1963) classifies these abilities as general fluid and general crystallized. Crystallized abilities indicate competence in integrating knowledge, which has been gained prior to the task thus crystallized. On the other hand, fluid abilities indicate tackling novel situations by adapting and recognizing patterns, rather than using crystallized knowledge. Most renowned fluid intelligence task is the Raven's Progressive Matrices (RPM), which is first introduced in J. C. Raven (1941) and subsequently improved and expanded (J. Raven, 2000). RPM became a non-verbal culture independent method to measure cognitive functioning. Another task to assess cognitive abilities is the n-back task which is introduced by Kirchner (1958). The N-back task assesses working memory capacity and its performance, so it is a rather specialized task. There are few other tasks which are similar to these tasks such as Digit Span Sequencing, Design Fluency Task, and so forth (Shakeel & Goghari, 2017).

2.1.1 Neural Correlates of Fluid Intelligence

The developments in imaging techniques motivated people to understand and measure intelligence by directly observing the brain. Detecting the brain areas, which are responsible for the activities we call intelligence, and measuring the individual differences are not a straightforward task. However, there are areas of interests, which, as many studies suggest, are involved in fluid intelligence. Neural correlates of fluid intelligence are typically studied by imaging people's brain during a fluid intelligence task.

In a study conducted by Haier et al. (1988), researchers investigated neural correlates of fluid intelligence by imaging participants with Positron Emission Tomography (PET) during an abstract reasoning task, and a vigilance task. They used Raven's Advanced Progressive Matrices (RAPM) as the abstract reasoning task, and Continuous Performance Test (CPT) as the visual vigilance task. For the control task they used a no-task version of the CPT. They found that both tasks activated the right-hemisphere of the brain. During both RAPM and CPT, the right parieto-temporo-occipital junction shows significantly higher metabolic activity compared to the CPT no-task condition. Furthermore, they also found some regional activations in the left-hemisphere during RAPM. In particular, they found that during RAPM, the left occipital cortex, and the left parieto-temporo-occipital junction show significantly higher metabolic rates compared to CPT and CPT no-task. Similarly, an increased glucose metabolic rate was observed in the left occipital lobe, during RAPM compared to CPT and CPT no-task. Haier et al. also investigated the correlation between glucose use and task performance, and found that RAPM performance has a significant negative correlation with overall glucose consumption of the brain. They argued that these finding could be interpreted as evidence for neural efficiency while noting that their sample size is small and they did not establish a proper baseline.

A study done by Duncan, Burgess, and Emslie (1995) investigated the impact of frontal lobe lesions on fluid intelligence. In this study, researchers studied patients with frontal lobe lesions to test whether fluid intelligence performance stayed intact after lesions. These patients are carefully selected, as they all have high IQ and socioeconomic status. They argued that Spearman's g (Spearman, 1927) obtained from a general test such as Wechsler Adult Intelligence Scale (Wechsler, 1955) failed to reflect the role of the frontal lobe in fluid intelligence as it contains crystallized intelligence tasks. They proposed that tasks such as progressive matrices and Cattell's Culture Fair (Cattell, 1973) are better suited to test the effect of frontal lobe lesions in general intelligence, as they are fluid intelligence tasks and they have a high correlation with Spearman's g. They tested patients and controls with WAIS and Cattell's Culture Fair. Although the patients scored similar to controls in the WAIS, they scored significantly lower scores in Cattell's Culture Fair. This suggests that frontal lobe lesions have little or no effect in g when tested with a general test, but has a significant effect when measured exclusively with fluid intelligence tasks.

In a study conducted by Prabhakaran, Smith, Desmond, Glover, and Gabrieli (1997) researchers investigated neural correlates of fluid intelligence by imaging subjects with fMRI devices. In this study, subjects performed RAPM and RSPM. They distinguished three types of problem according to Carpenter, Just, and Shell (1990), namely figural, analytic, and match problems. Figural problems consist of relations in attributes such as shape, number, and position. They require visuospatial analyses and require little or none analytic analyses. Analytics problems consist of analytic relations like formal operations such as logical OR, logical AND, and logical XOR. Match problems are control group problems. In match condition, there are no empty cells to be answered, instead, answers have one identical figure to answer cell, so participants only have to match bottom right figure to the identical copy given in the answers. Participants performed perfect score on match problems, nearly perfect score in figural problems (92.9%), and good scores (73.9%) on analytic problems. They found bilateral activations in frontal, temporal, and occipital analytic problems compared to figural ones. Furthermore, Carpenter et al. found lateralized activation in parietal regions of the left hemisphere. Figural tasks showed predominantly right side activations in frontal, parietal, temporal, and occipital lobes compared to the control tasks. They found the same activation patterns in analytic/control conditions in comparison to analytic/figural conditions. They argued that these patterns suggest that both figural and analytical reasoning processes employed during analytical reasoning. They concluded that the variety of activated regions, especially in regions, which mediates working memory, shows that why performance on Raven's Progressive Matrices predicts performances on a variety of tasks.

In Gray, Chabris, and Braver (2003) researchers investigated neural mechanisms which underlie general fluid intelligence. First, they assessed the participants by using Raven's Advanced Progressive Matrices. Then, they scanned their subjects by using fMRI during the three-back task. Three-back task is a version of the n-back task, where participants are shown a sequence of stimuli in a fixed interval, and they are tasked with deciding if the current stimulus matches the nth previous stimulus. They devised three conditions for the 3-back task, target condition, where the current stimulus matches 3-previous one, lure tasks, where stimulus matches a recent stimulus but not the target one, and non-lure tasks where stimulus does not match any of the previously seen stimuli. Subjects' performance were nearly perfect in non-lure trials (mean accuracy = 96%), similar in lure, and target trials (lure, 75%; target, 78%). Response times are similar in non-lure and target trials (non-lure, 919ms; target, 992ms) and longer in lure trials (lure, 1149ms). Subjects' performances during all conditions in the 3-back task were correlated with their performance in the fluid intelligence task (RAPM). They found no correlation between response times in 3-back tasks and performance in fluid intelligence task. They found sustained activity in lateral prefrontal cortex during tasks. This sustained activity covariate with *gf* during the lure trials but not during the control trials.

2.2 Review of Joint Action

Humans can perform a wide variety of tasks. Humans' ability to perform these tasks and mechanisms to perform these tasks in isolation have been studied extensively. However, a prominent ability of humans is the ability to perform most of these tasks cooperatively or competitively in a social environment. Humans coordinate and cooperate with each other in a variety of daily tasks. They combine their efforts to realize tasks, which they are incapable of doing as individuals, or they greatly improve the pace in which the task is done. Joint action is a form of interaction where multiple agents coordinate their actions to manipulate the environment (Sebanz et al., 2006).

Agents alter their behavior with respect to their co-agents in a social environment to perform a joint action. The nature of these tasks, whether they need mental effort or physical effort, changes according to if these tasks are performed in isolation or in a social environment, and performed individually or with the participation of other human agents. When these tasks are performed with the cooperation of multiple human agents, all agents, which involved in the performance, coordinate their efforts in a joint action. In this cooperation process, people can combine their distinctive efforts to create more complex workforce, or they can unify their same type of efforts to create more powerful workforce. For example, in a task where two people jointly build a Lego model with one of the participants gives instructions and the other builds the model (Clark & Krych, 2004), agents are responsible from different parts of the task. Completion of such tasks requires participants to combine their distinctive abilities to achieve a complex goal. In the tasks such as lifting a heavy object (Sebanz et al., 2006), participants combine and coordinate their physical forces to achieve the goal. Both types of cooperation require interaction among multiple agents' in order to create a common representational space. These common representations are important to ensure that the actions and goal (or multiple sub goals) are shared among the multiple agents, which got involved in cooperation. Using their interaction medium agents can exchange information to create a common ground and sustain their common ground during the performance of a joint action. For example, two agents can agree on a same name to call an abstract shape, which they both are not familiar. They can use this "common" or "shared" name to refer to the object during their cooperation. Usage of this "common" name can be specific to the task in hand, so that the agents can abandon the usage of this name after the task.

There are different types of joint actions. Studies argued that joint tasks cause alignment at different levels. This alignment does not necessarily have to be in the same level in which the task has been performed. Garrod and Pickering (2009) argues that the dialog is a joint action at different levels. They argued that alignment in one level causes alignment in another level. For example, when interlocutors use the same words in dialog they are inclined to align their grammars. Indeed Branigan, Pickering, and Cleland (2000) shows that when interlocutors use the same verb they are significantly more inclined to produce syntactically coordinated responses. Results in

Cleland and Pickering (2003) showed that people inclined to use same syntactic structure, which they are recently exposed. Furthermore, this effect is enhanced when both prime and target have the same head noun.Valdesolo et al. (2010) argues that inter-personal synchrony established by simple tasks can enhance the performance in more complex joint motor tasks, even those tasks are not connected. This means that the effects of inter-personal synchrony is sustained even after the termination of the synchronizing task. Studies such as Clark and Krych (2004) and Osaka et al. (2015) shows that the strength of interaction medium between co-participants significantly effects the task performance. These studies show that coordination and synchrony alter the internal state of the synchronized agents in neural level so that the effects of synchrony can be seen in multiple levels even after the synchronizing effects are disappeared.

2.2.1 Neural Correlates of Joint Action

Neural mechanisms that underlie joint action have been studied extensively across various domains. Many types of actions such as planning, moving, singing can be done in a joint or a cooperated context as well as in isolation. Fields such as Economics or Linguistics are more within the context of joint action, as they are mostly interested in interactions between multiple people. Studies such as, Rilling, Sanfey, Aronson, Nystrom, and Cohen (2004) and Tomlin et al. (2006) scanned people during economical exchange situations, while studies such as Stephens, Silbert, and Hasson (2010) scanned people while they were engaged with pre-recorded dialogs. Studies like Cui et al. (2012), Funane et al. (2011) and Osaka et al. (2015) investigates neural correlates of joint versions of simpler tasks such as, counting, button pressing, singing, and humming. These studies show that engaging in interactive tasks activates certain specific areas.

Performing a task with the participation of other agents changes the task. Most importantly, if multiple agents are involved in a task, whether in a cooperative or a competitive context, all agents are required to consider the other agents' perception and make inferences by it. Attributing mental states to self and others, and predicting the behavior of others is called Theory of Mind (ToM) (Premack & Woodruff, 1978). A series of brain networks and areas are associated with the ToM. Most notably,involvement of temporo-parietal junction (TPJ) is detected in several studies (Humphreys & Bedford, 2011; Saxe & Kanwisher, 2003). Involvement of superior temporal sulcus with social tasks is reported by multiple studies (Beauchamp, 2015; Gallagher & Frith, 2003; Saxe & Kanwisher, 2003).

In a study conducted by Rilling et al. (2004), researchers studied the neural correlates of theory of mind in an interactive economical exchange game. The study involves the Ultimatum and the Prisoner's Dilemma games played by two participants. The authors scanned one of the participant's brain with an fMRI device. Ultimatum game is a game which one of the participants divide a sum of money and the other participant either accepts or rejects the division. If the offer is accepted, both participants receive their designated amount of money, but if the offer is rejected, they receive nothing. The profitable situation for the second participant is to accept every offer, even if the offer seems unjust. In the Prisoner's Dilemma Game, both participants are given the choices to cooperate or not to cooperate and their profits are calculated by a combination of both their choices. In PDG, assessing the intention of their co-participants is a very important factor. In this study, researchers increased the profit of cooperation to increase the participants' incentive to cooperate. Participants interacted with human partners (in reality, they are pictures of confederates whom they are introduced earlier) and, computer (they are shown pictures of computer and a roulette wheel). For the control condition, they are asked to press a button to receive money. Each participant interacts with every partner only once. That means, in every turn of both games participants interacted with a different partner. Researchers found that in both games there is activation in the anterior paracingulate cortex and posterior superior temporal sulcus (STS). Furthermore, these activations are significantly stronger when the game is played against a human partner. They also detected activations in mid STS, hippocampus, posterior cingulate, and hypothalamus. These areas are associated with ToM abilities. An important finding of this study is that the regions, which associated with the theory of mind, are more active when interacting with a computer partner if the computer agent perceived to be sensitive to the choices of the human agent.

2.2.1.1 Hyperscanning Studies

Brain imaging has more than century old history. However, the overwhelming part of the brain imaging history is focused on the imaging of individuals. Studies have shown that during joint action, agents exhibit a degree of behavioral and neural synchrony. Simultaneous measurement of neural activity of multiple agents during an interactive task is called hyperscanning. Hyperscanning studies tries to quantify the mutual brain activation and synchronization in a social environment. Simultaneous imaging of two brains can reveal valuable information about both inter-brain and intra-brain activation patterns during a social task. The earliest example of hyperscanning is conducted by Montague et al. (2002) by using two fMRI devices in a competitive game. Researchers argued that simultaneously imaging of multiple participants presents us with an opportunity to detect relations between two brain imaging data, which cannot be detected by using behavioral markers. Hyperscanning methods are dependent on the economic accessibility of imaging devices and technological infrastructure of the experiments. Improvements on the availability of imaging technology, overall computing and network technologies increased the number of hyperscanning studies.

Recent studies, which utilize the hyperscanning method, are focused on the investigation of neural mechanisms involved in the social interaction. In a study by Dumas et al. (2012) researchers studied the inter-brain synchronization during social interaction. They conducted a simultaneous measurement of EEG during an interactive hand movement (gesture) task. Participants are instructed to move their hands with a meaningless gesture. They could see their co-participants hand movements through a TV screen. In each block, both participants are presented with a library of meaningless gestures. After participants are exposed to the set of gestures, they are told to imitate each other whenever they please. At the final phase of the block, one participant was instructed to imitate the other participant. Participants started each phase with no movement sub-block followed by no view sub-block. They assessed participants' imitation of each other with the co-occurrence of the same morphological gestures such as waving or drawing a circle. They labeled the data as synchrony, no-synchrony, imitation, and no imitation. They found inter-brain synchronization during the task.

In Tomlin et al. (2006) researchers measured hemodynamic response of two participants simultaneously. Measurements are done by using two fMRI devices in an economic exchange game. They find a systematic spatial pattern in cingulate cortex specific to the experimental condition, which includes a responding partner. This shows the possibility of existence of hemodynamic responses specific to the social interaction. These findings strengthen the arguments about the importance of concurrent imaging in a social environment.

In Cui et al. (2012) , researchers conducted simultaneous recording of hemodynamic activity by using Near-Infrared Spectroscopy (NIRS). During a simple "button pressing" task participants are observed in both competition and cooperation situations. In this task, participants are instructed to wait the go signal and then press a button. In cooperation condition, goal of the participants is to minimize the difference of their response time. After each trial, they are given a feedback which shows the difference in their response time and which participant responded earlier. In competition condition, their goal was to respond faster than their opponent did. After each competition, trial participants are given a feedback, which states that whether they win or lose. Researchers analyzed imaging data in terms of coherence. They found that brain-to-brain coherence is increased during cooperation. Furthermore, they found that coherence increase during the competition is not significant, which shows that the measured coherence cannot be solely a result of similarity of concurrent action but derives from effort for cooperation. This study also has important methodological contributions. This study is one of the earliest hyperscanning studies, which is conducted with NIRS. Earlier hyperscanning studies are conducted using fMRI and EEG. Although hyperscanning with these imaging techniques yielded important results, both techniques have important limitations. fMRI studies are unable to present a natural social environment to the participants. Researchers argued that the environment, which NIRS offer, has more ecological validity. EEG is a widely used neuroimaging method; however, it has a poor spatial resolution. Apart from contributions on imaging methods, this study also proposes Wavelet Transform Coherence (WTC) as a method to quantify inter-brain coherence, which became a frequently used method.

A research conducted by Osaka et al. (2015) is another example of hyper-scanning study conducted with fNIRS. Two participants' hemodynamic responses observed in a cooperative singing task. The experiment consists of two different conditions. The first condition is face-to-face (FtF) condition where participants sing a song and hum together while facing each other. In the second condition, devised as face-to-wall (FtW), participants again sing a song and hum together, but in this condition, both participants faced to a wall. Apart from controlling interaction medium, researchers also controlled the participation to joint action. In each experimental set, participants conducted single singing (or humming), cooperative singing, and sing-listen tasks. They used Wavelet Transform Coherence analysis to determine inter-brain coherence of oxy-HB signals of participants. They detected increased coherence between the left Inferior Frontal Cortex during both cooperative singing and humming tasks. Furthermore, they detected increased coherence in the right IFC during humming task. These coherence values are not detected during analysis of single tasks and random pairs. These findings indicate IFC is responsible in neural synchronization.

In the study which conducted by Funane et al. (2011), researchers studied brain activities during a cooperative counting task. They measured hemodynamic activities of two participants by using two fNIRS simultaneously. Participants were tasked with counting to ten in their minds following a start cue. After the counting process is done, participants were tasked with pressing a button. To make the task cooperative, participants are sat in a face-to-face position and instructed to press the button as synchronized as possible. Therefore, participants were to adjust their counting speed with respect to each other to make the button pressing synchronous. A feedback of time difference between button pressings is given to participants in order to inform them about their performance in the task. Researchers calculated activation values for each fNIRs channels in rest and task conditions by using mean, variance, and length of the oxygenation values. They found relations between participants' task performance and spatiotemporal coherence of their NIRS signals.

Summary

In conclusion, the research on both general fluid intelligence and joint action have a long history. The ability to tackle fluid intelligence problems are widely investigated, because, in general, it reflects an individual's ability to tackle novel problems. Although people often tackle problems in a cooperative and social environment, the ability to tackle novel problems in a cooperative environment and its neural correlates are rarely investigated. Hyperscanning is a recent development in neuroscience methodology, which allows researchers to investigate the neural mechanisms of joint action by imaging multiple people simultaneously during a task. In recent years, hyperscanning became a popular method to investigate the neural correlates of joint action. To the best of our knowledge, there are no studies regarding the neural mechanism of joint action during a fluid intelligence task. The research questions in this study, aim to contribute joint action literature by investigating one of the least studied forms of joint action in a hyperscanning setup.

CHAPTER 3

MATERIALS AND METHODS

Joint fluid intelligence experiment

A Joint fluid intelligence task is designed to investigate brain-to-brain coherence. This experimental protocol is explained in this chapter.

3.1 Participants

The participants are Turkish speaking, right handed males with no neurological and psychological problems. Participants are given the Edinburgh Handedness Inventory (Oldfield, 1971). We conducted 17 pair experiments (34 people). 3 experiment pairs are discarded due to poor data quality. Participants are college students, which are gathered through online advertising. All participants given 20 TRY for their time and contribution. Resource for monetary incentive is provided by TUBITAK.

3.2 Experimental Setup and Devices

Subjects were present in the same room during the experiment. Room was secluded from sunlight and illuminated by fluorescent light bulbs. Experiment setup consists of two desktop computers with 24-inch 1080p displays. Each subject is observed by a fNIRS device, there are two fNIR devices in the lab one is model 1000 and the other is model 1200. Both devices use the same sensor pads, which come with model 1200. fNIRS setup which used in the experiment can be seen in figure 3.1. Both participants' gazes are tracked by using EyeTribe eye tracker. Participants sat side-by-side against the wall. Questions are presented by a custom program written in Python 3.4. This custom program uses PyGaze library (Dalmaijer, Mathôt, & Van der Stigchel, 2014) to handle eye tracking and stimulus presentation. A network connection between two computers is used to exchange synchronization markers and gaze point between two participants. UDP protocol is used to realize this communication process. Figure3.2 depicts the experimental setup.

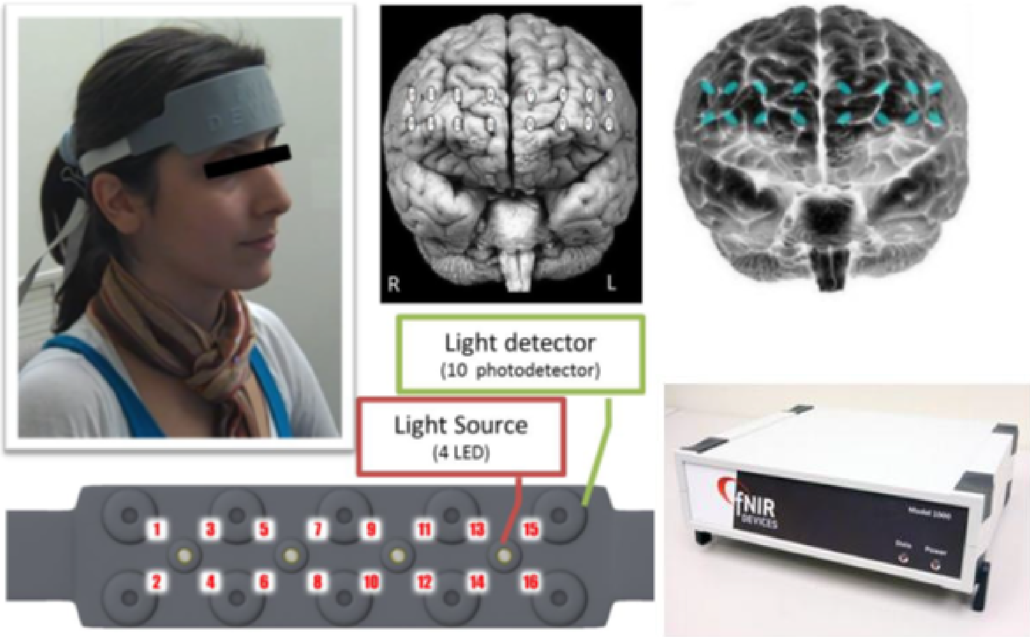


Figure 3.1: Sensor pad, and optode layout (Left- Top right), fNIR Devices 1000 (Bottom right).

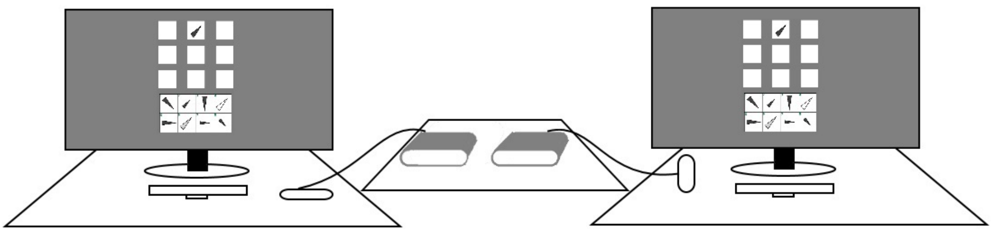


Figure 3.2: Dual fNIRS and Eye Trackers setup.

3.3 Experiment protocol

In the experiment, participants solve fluid intelligence task. The task is to solve Sandia matrices (Matzen et al., 2010). In order to force participants to cooperate during the experiment, questions are presented as closed. Participants have their gaze tracked. In order to open a fragment of question each participant had to look in the same fragment of the question. When both participants are fixated on the same fragment of the question, this fragment is opened. Opened fragment remains open as long as both participants preserve their fixation on the opened fragment. When one or both of them loses fixation on the fragment, fragment closes again. Each participant also given a cue of his co-participant's gaze position. When each participants fixates on a different fragment of the question, they see each other's targeted fragment highlighted with a red frame. Example of experiment screen can be seen in 3.3. In 3.3, left screen shows the situation which both participants fixated in fragment 2, middle screen shows the screen of a participant whose co-participant fixated on fragment 6, and the last screen shows the situation which both participants fixated on fragment 6. Answer fragment always remain open. Participants use numeric keys from the keyboard to select their answer to question. When they select an answer, the answer is highlighted with a green frame. Participants can change their answers using same input configuration. Question remains until a participants hit the enter key or until the designated timeout period of 3 minutes runs out. Participants are instructed to avoid head movements for ensuring the quality of both fNIRS and eye tracker recording. However, participants are free to converse with each other. They are expected to agree on a same answer for the questions but they independently give the answer input. There 1 open question for every 3 closed question. In the open questions, all fragments of the question presented openly so fixating the same fragment is not mandatory for the open questions. There are 12 closed and 4 open questions in addition to 1 open and 1 closed practice questions.

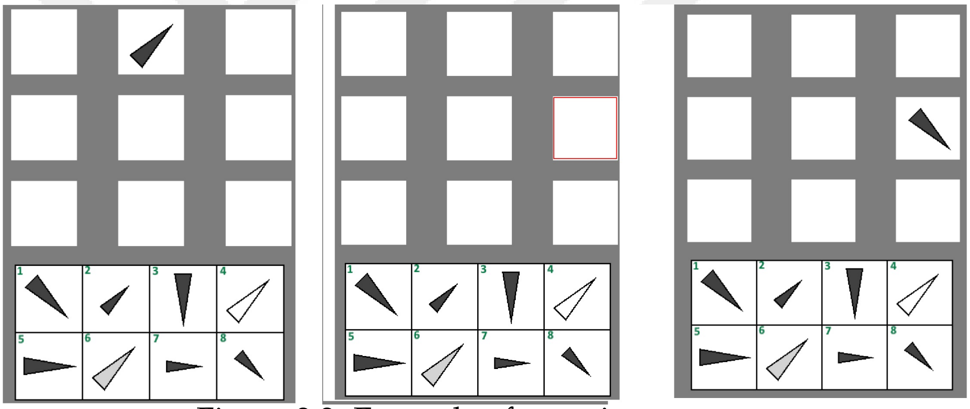
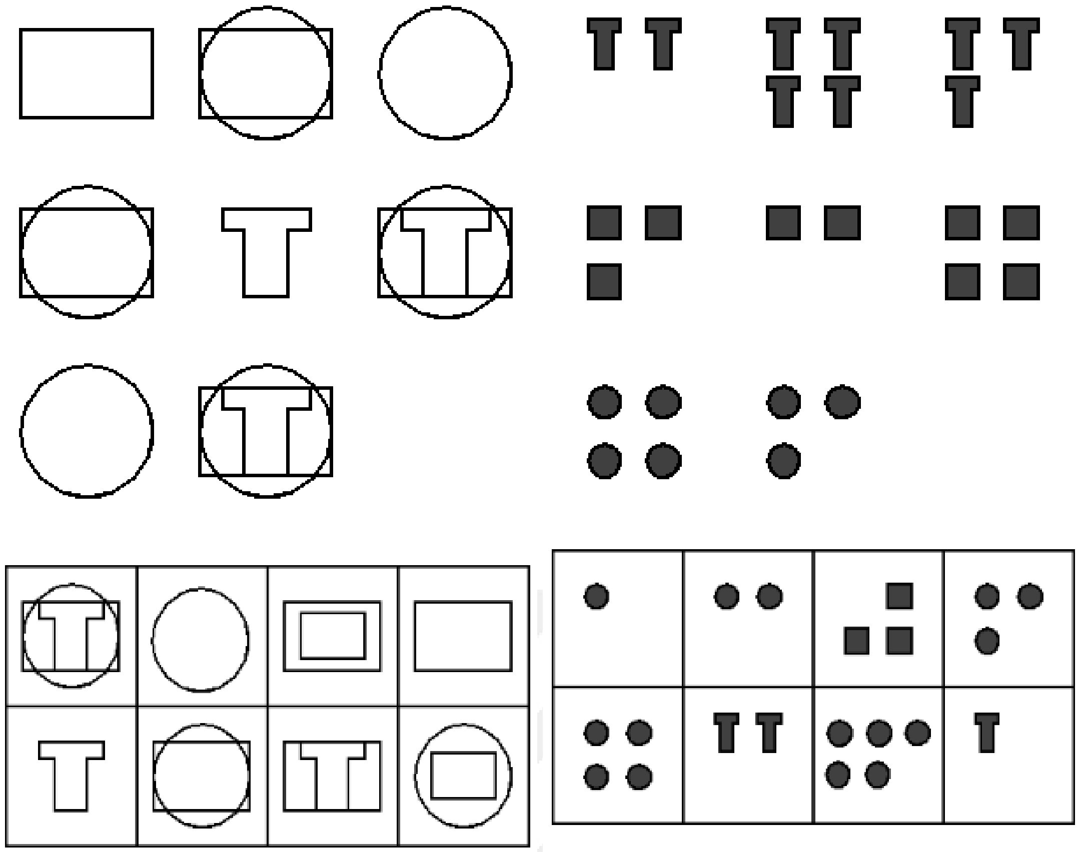


Figure 3.3: Example of experiment screen.

3.4 Question Types

There are 4 types of questions presented in the experiment. These type categorizations are made by (Matzen et al., 2010). There are X type of patterns and 3 level of difficulty in the first 3 type of questions. These difficulty levels are determined by the number of different relationship needed to recognize to solve the problem. For example, level 3 question means that there are 3 types of relation in the question such as shape, color, orientation. Additional to these 3 level there is forth level of logic questions. These logic questions consist of "AND", "OR", and "XOR" relations. All experiments are conducted by using the same question set selected from a larger dataset. Example of two questions can be seen in figure 3.4.



(a) XOR (b) Level2

Figure 3.4: Example of XOR (a),Example of Level-2 (b).

3.5 Experiment Flow

There are two sections of the experiment. The first section is the practice part. In this part, participants are presented with one open and one close question. In the practice part questions and experiment flow are described to the participants and participants' questions about the running of the experiment are answered. If a there are any problems which may hinder the experiment flow they are handled before proceeding to the experiment part. In both sections input outputs methods are identical. Before every question presented participants' computers are synchronized by a UDP connection. Immediately after the synchronization, process start markers are sent to both fNIRS devices. However, the experiment part has few additional mechanics. Different from the practice part, experiment part has rest periods and calibration checks. Before every question, participants are presented with a blank screen with a fixation mark in the center. This rest period has a duration of 20 seconds. In this rest period, participants are allowed to close their eyes. A brief beep sound played after the rest period to alert participants for the presentation of the question. After every question subjects are presented with a drift check to test if the calibration is still intact, where they asked to fixate on a point in the center of the screen. If there were 60 samples in the selected radius from the center point, drift correction would be passed successfully.

However, if there are more than 20 consequent samples which are not within the designated area, counter for 60 samples are reset. If a subject cannot pass the drift check within 10 seconds, a calibration screen would be presented. Moreover, if subject cannot pass the drift check at all, a calibration would be triggered manually by hitting the escape key. A diagram depicting experimental flow can be seen in 3.5. Question order in the experiment part is randomized across the experiments but question order in the practice parts are same for every experiment. Randomized experimental sequences filtered to ensure that there are exactly 3 of each type of questions presented as closed questions and 1 of each type of question presented as open questions.

3.6 Dual Eye tracking

In this experiment, a fluid intelligence task modified to a joint task using dual eye tracking as a restrictive condition. Both participants' gaze positions were tracked using EyeTribe eye tracker. These gaze positions are used for forcing participants to cooperate. Moreover, they are also analyzed to measure cooperation between the participants. Details of the role of the eye tracking during the experiment and as a measure detailed in following sections.

3.6.1 Eye tracking in fluid intelligence task

Eye tracking is essential for the joint fluid intelligence task. Eye tracking is used to ensure that participants cooperate at least to some degree. In the experiment, participants are presented with the problem with hidden information and they need to reveal the hidden information by coordinating their gaze positions with respect to each other. Participants are given a cue of their co-participant's gaze position. Experiments starts with calibration process to ensure that participants gaze positions are correctly measured. 9 points calibration process is used in calibration. During calibration, participants instructed to look to black point presented in experiment screen. An error measured for each point. Quality of the calibration tested and corrected if necessary after each trial to ensure that quality of the calibration preserved. Additionally, calibrations can be manually triggered upon participants' request. Experiment program listens EyeTribe's local server for raw pixel coordinates of the gaze position. Then it maps gaze positions to discrete fragments of the experiments. Using a UDP connection between two computers two experiments programs exchange participants' gaze positions as currently fixated fragment numbers. Then each program compares local and remote gaze positions to check if the positions are identical. If gaze positions are identical, program draws stimulus, with targeted fragment open and all other fragments, except answer sheet, closed. If targeted fragments are different, each program draws the stimulus with all fragments except answer sheet closed, in addition it draws a highlighting frame on remote gaze position to inform participants about their co-participant's gaze

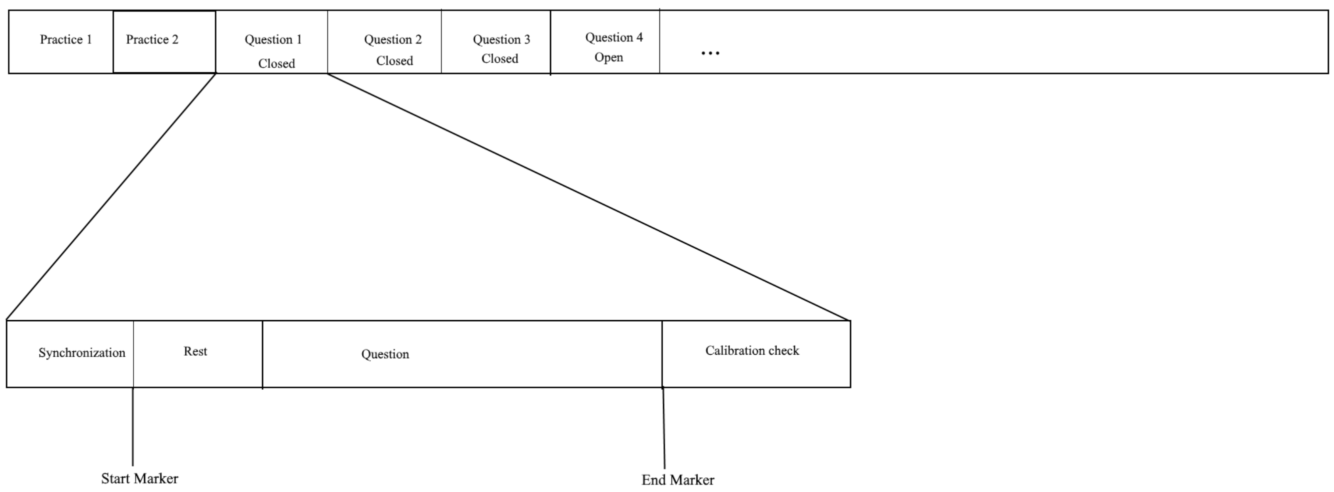


Figure 3.5: Diagram of experimental flow.

position. In each cycle program logs local and remote target with timestamps. This log files also include participants' answer to questions. We can define a cycle as sampling gaze data, converting gaze data to fragment number, exchanging fragment number, drawing stimulus, logging data. Each cycle takes about 100ms; however, as it highly dependent on computers processing power and network connection, it can take 50ms to 150ms. Data exchange done by a different thread than other parts of the experiment, connection thread and experiment thread communicates via a queue. If experiment thread fails to produce new fragment number before new exchange process happened, last fragment number would be used again.

3.6.2 Eye tracking Data

Eye tracking data and experiment responses are together constituting behavioral data of the joint fluid intelligence task. We used processed eye tracker data instead of raw pixel data. Experiment software handles the process of converting raw pixel data to discrete experiment fragments. Eye tracking data is consisting of discrete experiment fragments. There are 10 fragments, which are logged in eye tracking data, fragments 1-9 are fragments of the question and fragment 10 is the answer sheet. Note that the answer sheet is always open. Raw pixel values, which do not correspond to a designated fragment position, is marked as -1. A custom python script is used to smooth eye tracking data by converting each -1 to last fixated meaningful fragment (1-10) before that -1 is encountered. Eye tracker data gathered in this experiment is consists of discrete points with timestamps, which indicates the experiment fragment fixated in the corresponding time. Each participant of each experiment has an eye tracking data output. These output files have timestamps, local target and remote target. This means each participant's data file also stores their co-participants eye tracking data. Both eye tracking data and experiment data (question names, answers) stored in the same file. A custom python script is used to extract eye tracking data, and experiment log from single log file. Eye tracking data is smoothed by using same python script. Output of this script is a single eye tracking data file which is created by concatenation of experiment blocks (practice blocks are discarded), a time data file which consists of starting and ending points of each block as data point, and an experiment log data file which consists of question sequence, participants' responses to the questions and correctness of the responses.

3.6.3 Eye Tracking Data analysis

A dataset created by processing raw eye tracking data. This dataset consists of 17 processed and reconstructed eye tracking data. Reconstructed data means all blocks extracted from experiment log file, then concatenated to a single file consists of eye tracking data. Note that experiment produces an output file for each participant. However, since every participant's computer also logs their co participant's eye tracking data, only one log file is used for each experiment. For each experiment, coherence values are calculated by using Wavelet Transform Coherence. Coherence values are calculated by a series of MATLAB scripts. Sampling rate of experiment is not constant throughout the experiments and during experiments. Sampling rate of experiments varies from 7-15 samples for seconds with an average sampling rate of 10 samples/second. Block coherence are calculated by taking arithmetic average of WTC output which falls into block start and end in time domain, and 128-256 Hz in frequency domain. A coherence value is calculated for each block of each experiment. Details of WTC analysis is addressed in WTC section.

3.7 fNIRS Hyper-scanning

In the experiment, two participants are given with a joint fluid intelligence task. During this task hemodynamic changes in each participant's prefrontal cortex recorded by using two fNIRS devices.

Functional near-infrared spectroscopy (fNIRS) is non-invasive, continuous, and portable neuroimaging method, which tracks the changes in blood volume and oxygenation of human brain (Izzetoglu et al., 2005). Brain activations are determined with the changes in oxygenation. Using oxygenation as a parameter to determine neural activity is based upon the relation between cerebral activity and functional brain activity, which is called as neurovascular coupling (Obrig et al., 2000). In recent years, fNIRS became established method to reliable method to measure oxygenation in the brain. fNIRS as a non-invasive imaging technique provides opportunity to safely measure brain activity in affordable and portable fashion. fNIRS, compared to other neuroimaging techniques, in a balanced position when it comes to the equilibrium between spatial and temporal resolution. Figure 3.6 depicts the comparison of fNIRS with other non-invasive neuroimaging techniques (Strangman, Boas, & Sutton, 2002).

fNIRS technique used certain wavelengths of light to measure changes in the oxy-hemoglobin and deoxy-hemoglobin concentration. Near-infrared light can easily penetrate the skull and scalp, so it can be used non-invasively measure the changes in the tissue (Jobsis, 1977). fNIRS uses specific sensor and light source placement geometry to specifically determine the hemodynamic changes in the brain tissue. This specific geometry allows us to track photons which traveled in a banana shape path through the tissue which we want to image. Figure3.7 (left) shows the representation of sensor placement and path of light. fNIRS uses wavelengths of light which range between 700 to 900 nm, in this spectrum hemoglobin is a strong absorber, and importantly most of the tissue material specifically water is transparent. Figure 3.7 (right) depicts the absorption factor of oxy-hemoglobin, deoxy-hemoglobin, and water.

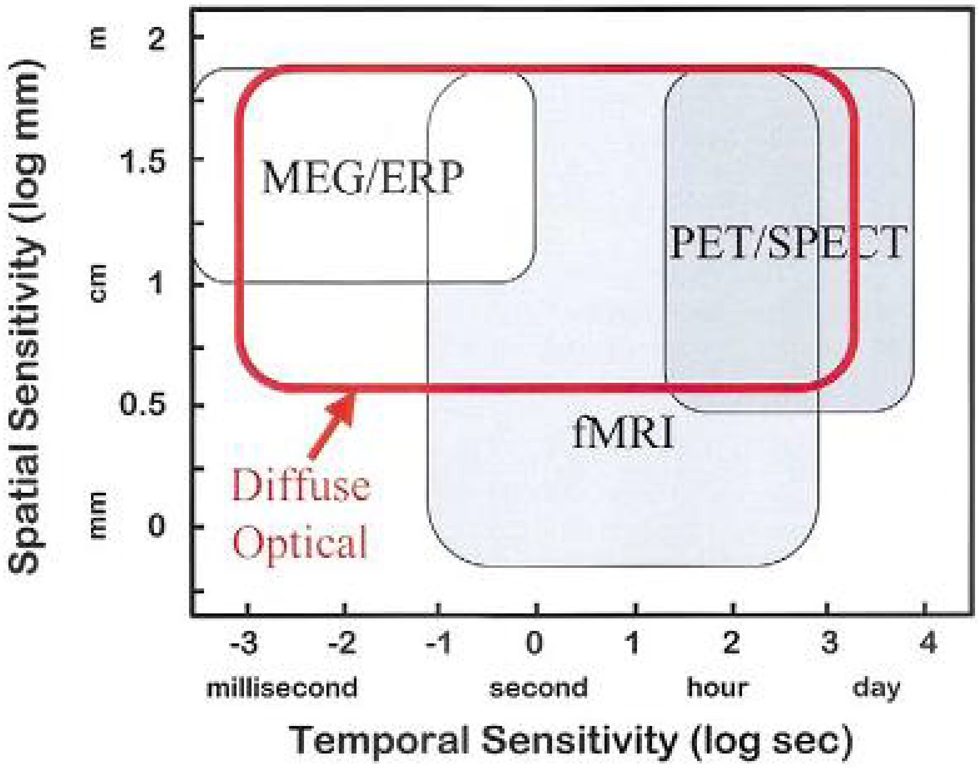


Figure 3.6: Comparison of spatial and temporal sensitivities of non-invasive neuroimaging methods. Reprinted from Gary Strangman, David A. Boas, and Jeffrey P. Sutton (2002). Non-Invasive Neuroimaging Using Near-Infrared Light. Biological Psychiatry, 52, 679-693.

3.7.1 fNIRS recording

During the joint fluid intelligence task, each participant is recorded with an fNIRs device to measure hemodynamic activities at their prefrontal cortex. fNIR devices model 1000 and model 1200 used in this process. In both devices, we used same sensor pads, which come with model 1200. Both sensors have 4 led light sources and 10 detectors, which allow us to collect oxygenation measures from 16 points (optodes) on the prefrontal cortex. Both experiment computers use COBI Studio software (Ayaz et al., 2011) to collect and store experiment data. We collected data in 2Hz sampling frequency. Before starting the experiment, both sensors set up. Sensors are adjusted and controlled to ensure there is a gap between sensor pad and the subject's forehead, and no hair is interfering with led and detectors. Sensors parameters of led current and detector gain are tuned to acquire an optimal signal to noise ratio. After setting up the sensor and adjustments are done, an experiment is created in COBI Studio. Afterward, participants are instructed to stay in a resting state, where participants are stands still with their eyes are closed. In resting state, a baseline is triggered. After baseline COBI Studio starts the data recording.

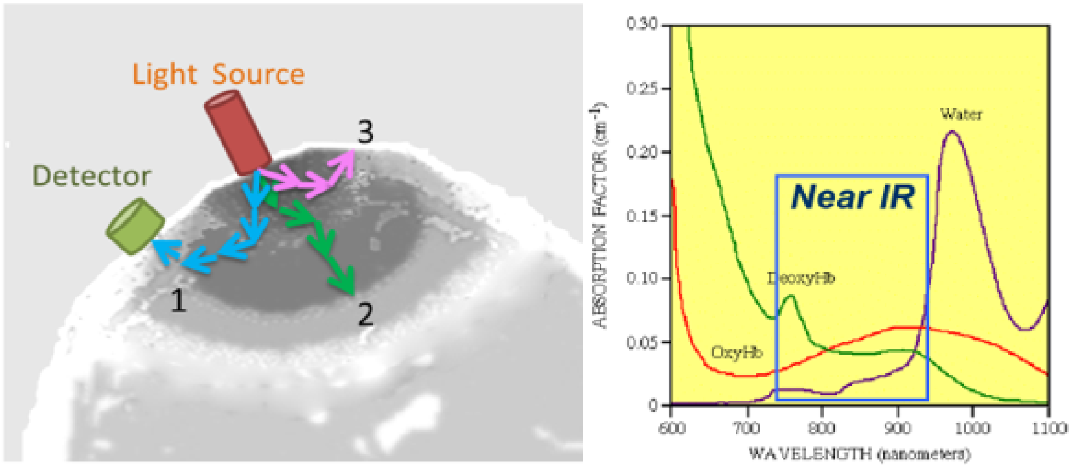


Figure 3.7: Sensor detector geometry (left), absorption factor of NIR (right).

3.7.2 fNIRS Data

fNIRS data is collected by using COBI Studio data collection software (ref COBI). In each block, experiment software sends a start and an end marker to COBI Studio. After the recording is done, COBI Studio saves the data and marker files. Data and marker files are processed by using fnirSOFT software. fnirSOFT software allows us to inspect and process the data. Since there are multiple experiment files, an fnirSOFT script used to process the data as a batch process. This script takes the nir files and marker files, applies FIR (Finite impulse filter) with window size of 2Hz to raw lightgraph data, divides data to blocks by using markers, and calculate oxygenation by using the first 20 seconds as baseline and method of MBLL (Modified Beer-Lambert Law). Script has 5 output files for each experiment block (each nir and marker file). Four of these outputs are metrics of hemodynamic changes namely, difference in oxyhemoglobin concentration (hbo), deoxyhemoglobin concentration (hbr), total hemoglobin concentration (hbt), and oxygenation concentration (oxy). The last output files are time file, which consists of markers with corresponding timestamps. Each block data of each experiment is extracted as csv files. After extracting these files, a custom python script is used to concatenate these files to a single file. Additionally, another fnirSOFT script is used to extract these hemodynamic metrics for each experiment as single block. This script takes an experiment data (nir file), filters it by using FIR filter, calculate oxygenation with respect to global baseline (baseline is taken in start of the experiment), then detrends it for compensating global trends in data (this detrending process mimics local baseline). This process yields a single output file for each hemodynamic metric and a time file. Raw experiment data are processed by using fnirSOFT software. Output of the processing yields 10 processed experiment data for each experiment. For the first process, we acquired, for each experiment, 4 reconstructed hemodynamic data file and a time data file. Reconstruction means concatenation of blocks to a single file. For the second process, for each experiment, we acquired 4 hemodynamic data file, and a time data file.

3.7.3 fNIRS Data analysis

A dataset is created by processing raw light intensity data. This dataset consists of 5x17x2 a total of 170 files (136 hemodynamic data, 34 time data) collected from 17 pairs, and 5x8 a total of 40 files (32 hemodynamic data, 8 time data) collected from 8 single participants. Coherence values are calculated by a series of MATLAB scripts and Wavelet Transform Coherence (WTC) is used as a method of coherence calculation. Outputs of the WTC scripts are coherence and coherence increase values of each optode in each block. Coherence values of questions are analyzed in accordance to question types and open/close conditions. Details of WTC analysis is addressed in the WTC section. Both single and pair experiments are analyzed by using load calculation methods. Load values are calculated by taking arithmetic means of hemodynamic values in each block.

3.8 Multimodal Recording

In the joint fluid intelligence task, we used eye tracker and fNIRS simultaneously. Since both devices use infrared to collect data, there are interference between two modalities. Specifically, infrared rays emitted by the eye tracker greatly interferes with fNIRS data collection. Interference is measured by the magnitude of ambient light coming to the sensors. In an unshielded data collection setup, interference is too high to collect a healthy experiment data. Lower channels are the most affected by this interference. We tried to reduce the interference by adding an extra headband over the fNIRS sensor pad. This extra headband is simple aluminum foil wrapped in a piece of cloth. This countermeasure greatly reduced the interference of eye tracker on fNIRS. Furthermore, it added additional isolation against other sources of ambient light and supported sensor pad. Effect of eye tracker on fNIRS signal, and effectiveness of foil headband can be seen in Figure 3.8. However, we could not achieve total isolation without disturbing the participants. Increasing the thickness of the foil helps us to isolate more of the interference, but weight of the sensor and wrapping, observed to cause headaches in participants, thus disrupts experiment experience.

3.9 Wavelet Transform Coherence

Wavelet Transform Coherence (WTC) used to calculate coherence values in both neuroimaging and eye tracking data. We used MATLAB library presented by (Grinsted, Moore, & Jevrejeva, 2004) to calculate WTC. Using WTC to calculate coherences of two fNIRS signal yielded promising results in several studies (Cui et al., 2012; Osaka et al., 2015). Wavelet Transform Coherence produces a 2-dimensional matrix of coherence values. These coherence values are between 0-1. Each column is a vector of coherence values in a time point. Time point, in that case, is a single sample. Each row

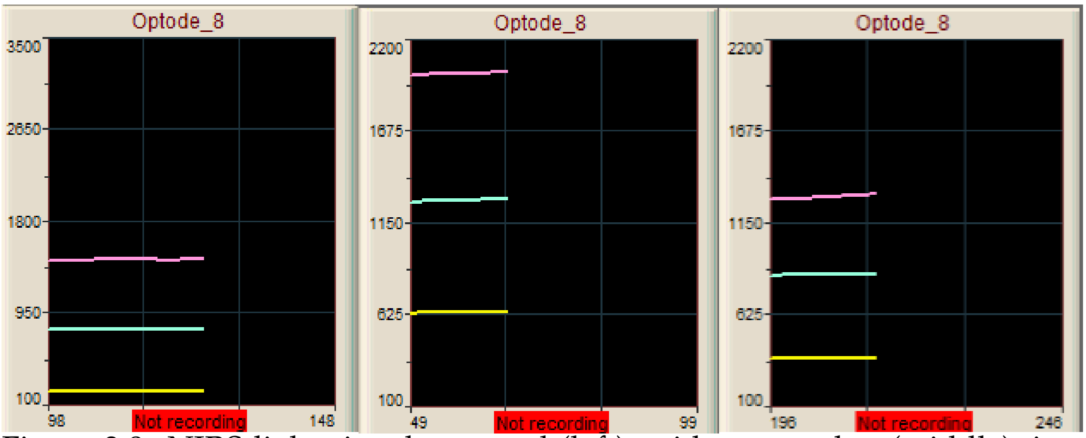


Figure 3.8: NIRS light signals, normal (left), with eye tracker (middle), isolated (right).

is a vector of coherence values in a given frequency where each element is a coherence value in a time point. Naturally as the frequency decreases (therefore period increases) number of meaningful coherence values can be used is decreases. For the calculation of final coherence values, a time window and a period window should be selected. These boundaries create a rectangle in the 2D coherence matrix. Start point and end point of each block are selected as time window. For selecting frequency window Duration of questions taken into account.

Sampling rate of fNIRS device was constant 2Hz throughout the experiments and during experiments. A period window of 32-64 is selected to calculate block coherence. 32-64 samples correspond to 16-32 seconds. 16-32 seconds is selected because it covers the average duration of 1-level relation tasks (20 seconds). 1-level relation questions are designed to be answered in one iteration. Therefore, we selected average duration of 1-level questions as our coherence window. Time files are used to determine beginning and end of each block. Block coherence are calculated by taking arithmetic average of top 10% percent most coherent data points, starting from 3 seconds after question is presented, in WTC output which falls into block start and end in the time domain, and 32-64 in frequency domain. A coherence value is calculated for each block of each experiment for all 4 hemodynamic parameters. The first 3 seconds of block is taken as rest period for calculation. We shall note that this 3 seconds period is 3 seconds which follow the actual 20 seconds rest period. Taking the first 3 seconds of block as a rest period, instead of actual rest period is to eliminate the coherence which persisted from previous block. Average of coherence of these 3 seconds is taken as rest coherence. Then, a coherence increase value is calculated by subtracting the rest coherence from the block coherence.

Eye tracker data is sampled each time the experiment redraws the experiment screen. In each sampling, experiment logs the experiment fragment, which corresponds to sampled gaze position. Sampling rate of experiment is not constant throughout the experiments and during experiments. Sampling rate of experiments varies from 7-15 samples for seconds with an average sampling rate of 10 samples/second. A period window of 128-256 selected to calculate block coherence. 128-256 samples correspond to 12-26 seconds. 12-26 seconds covers the duration of coherence window, which we selected for fNIRS data analysis. Block coherences are calculated by taking arithmetic average of WTC output which falls into block start and end in the time domain, and 128-256 in frequency domain. A coherence value is calculated for each block of each experiment. Figure 3.9 shows the comparison of WTC and common gaze points. In figure 3.9 top figure shows the average coherence values in 128-256 period window, in bottom figure data points which two participants fixated on same question fragment showed as 1 other data points showed as 0.

3.10 Summary of Methodology

In this study, brain-to-brain coherence of two participants investigated during a joint intelligence task. As a fluid intelligence task, Sandia matrices are selected. The task is converted to a joint task with the help of dual eye tracking system. During the experiment, both participants' prefrontal cortices are imaged by using a dual fNIRS setup. Both neuroimaging and eye tracker data are preprocessed and used in coherence calculation. As coherence calculation method, Wavelet Coherence Transform (WTC) is used. Additionally, neuroimaging data is used in load calculation. Presentation of experiment and preprocessing of the data are done by Python scripts. Coherence calculations and load calculations are done by MATLAB scripts. Processed data are analyzed according to question types, and open/close conditions. Analyses of the experimental outputs are addressed in the following chapter.

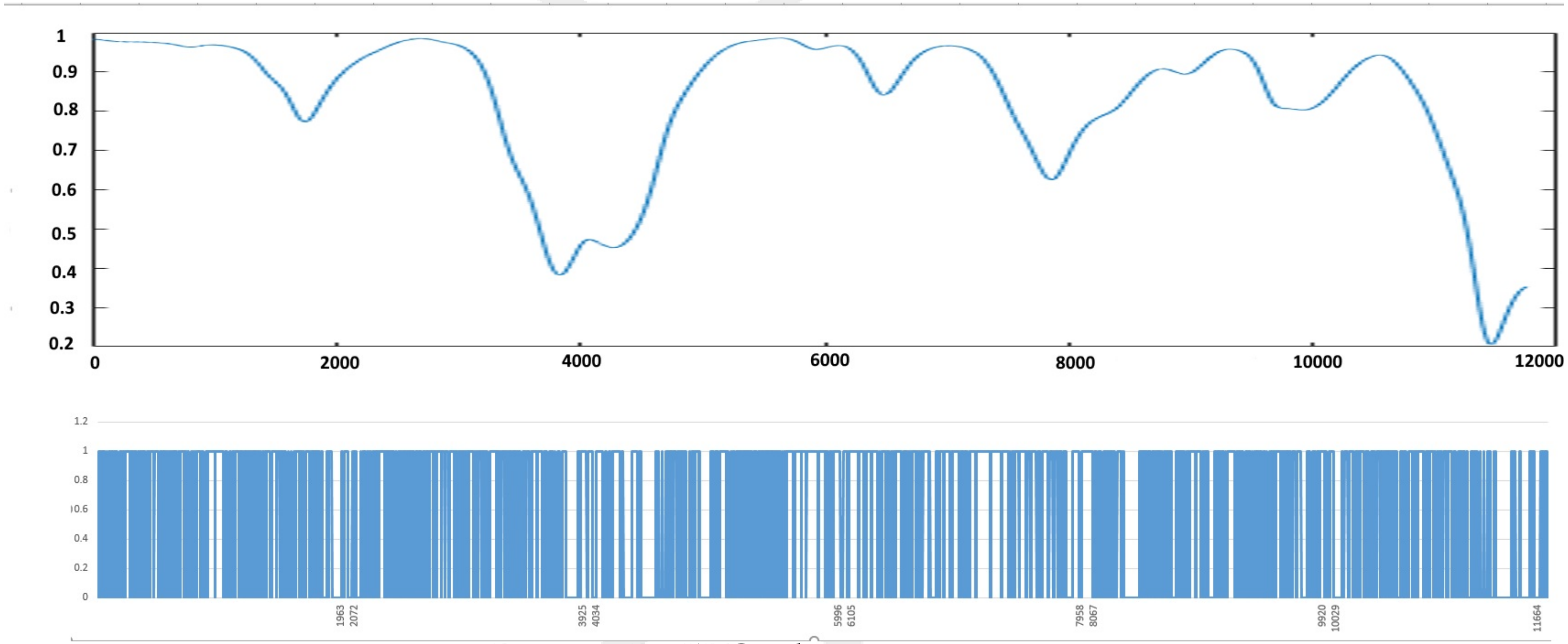


Figure 3.9: Eye WTC and common gaze points.

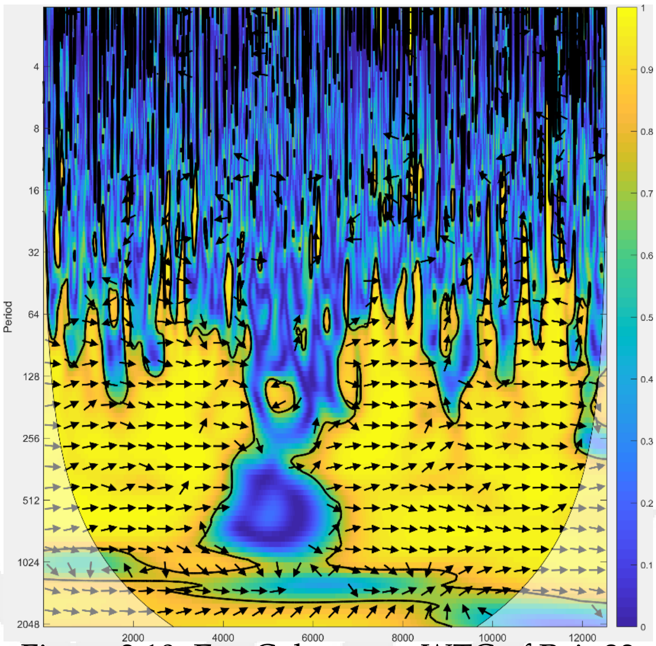


Figure 3.10: Eye Coherence: WTC of Pair 23

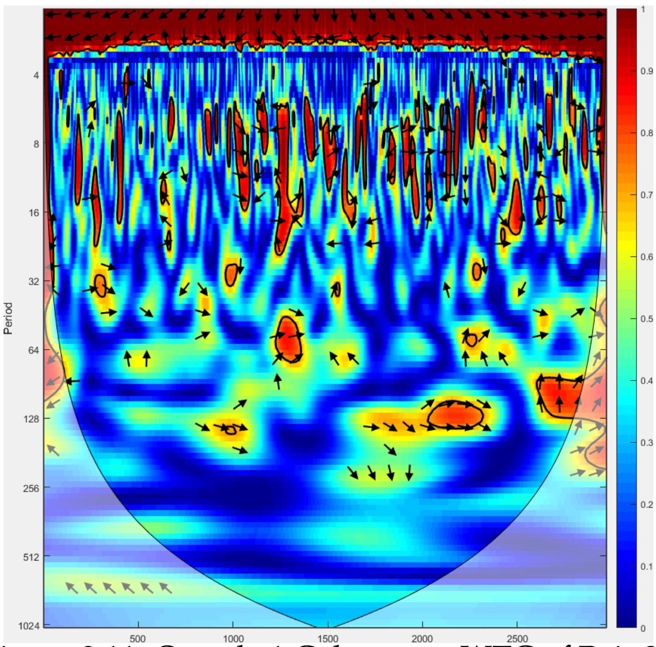


Figure 3.11: Optode 1 Coherence: WTC of Pair 23

CHAPTER 4

RESULTS

This chapter contains results of the joint fluid intelligence experiment. The results are addressed in three parts. These parts are behavioral analysis, coherence analysis, and mental load analysis. In behavioral analysis, coherences of eye movements are calculated by using WTC. Eye coherence values and success rate of questions are analyzed with respect to question type and open/close conditions. For coherence analysis, coherence increase values are calculated by using WTC. These coherence increase values for all 16 optodes in 4 hemodynamics parameters are analyzed with respect to question types, and open/close condition. These hemodynamic parameters are changes in the oxy-hemoglobin, deoxy-hemoglobin, oxygenation, and total changes in hemoglobin. For mental load analysis, average change in hemodynamic parameters for all 16 optodes are used to determine mental load. These load values are analyzed with respect to question types and open/close condition.

4.1 Behavioral Analysis Results

Behavioral results of joint fluid intelligence experiment are addressed in this part. Eye tracking data are discretized and eye coherence values are calculated by using pair of data from each experiment. Eye coherence values are calculated by using WTC. During closed questions eye coherence values are significantly higher than open questions. Figure shows the mean eye coherence values during open and close questions.

The independent variables are the problem type and whether gaze togetherness was needed to solve the problem (i.e. open and closed). Problem type was considered at two different levels. At the first level we distinguished 2 different types of problems, namely combination and logic puzzles, whereas in the second level we consider 3 types for each large category, namely puzzles that require one, two or three pattern combinations and logic puzzles implementing AND, OR and XOR patterns.

At the behavioral level we consider correctness, response time and eye coherence levels as the main dependent variables.

4.1.1 Accuracy

The bar chart displayed in Figure x below shows the mean accuracy of the pairs in the sample in each puzzle type. Overall, the pairs performed close to ceiling for the combination type puzzles that required one, two and three pieces of information. A Greenhouse-Geisser corrected repeated measures ANOVA conducted over the mean accuracy percentage indicated the difference among the task types were significant, F(2.39, 31.01)=6.77, p<.01, partial η^2=.34. Sidak corrected pair-wise comparison indicated that this difference is due to tasks Combination-One & Logic-XOR (Mean Difference=.25, p<.05), Combination-Two & Logic-XOR (Mean Difference=.29, p<.05) and Combination-Two & Logic-AND (Mean Difference=.57, p<.05).

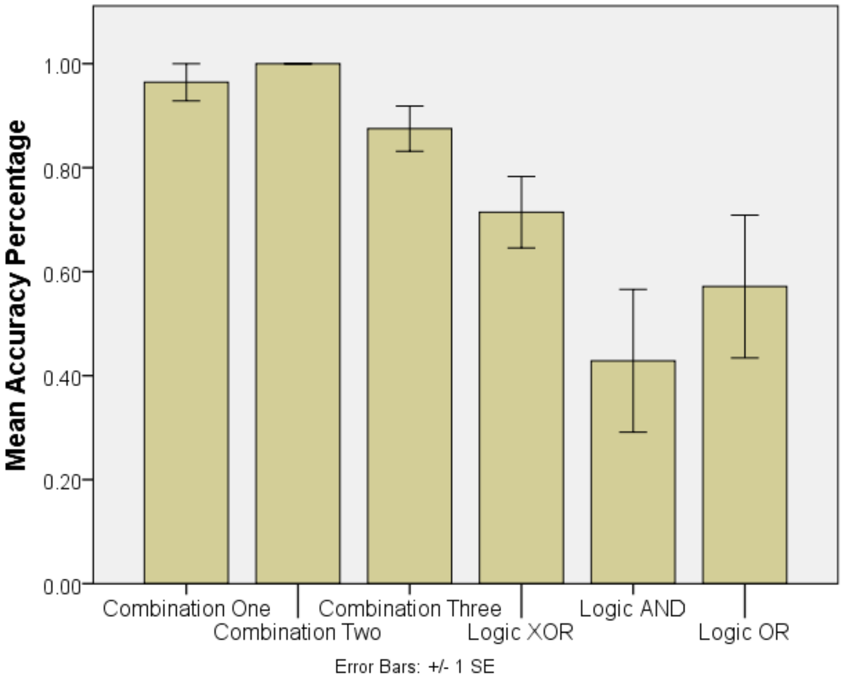


Figure 4.1: Percentage of mean correct answers according to questions types.

4.1.2 Response Time

The bar chart in 4.2 below shows the average time it took the pairs to collectively respond to each puzzle type. A Greenhouse-Geisser corrected repeated measures ANOVA conducted over the mean response times indicated that there is a significant difference among the task types, F(2.46, 31.95)=13.70, p<.001, partial η^2=.51. Table 4.1 below shows the significant Sidak corrected pairwise comparisons. The pairwise tests suggest that the partners spent significantly more time on logic type puzzles.

Table 4.1: Pairwise Comparisons

(I) Puzzle	(J) Puzzle	Mean Difference (I-J)	Std. Error	Sig.b	95% Confidence Interval for Difference	
					Lower Bound	Upper Bound
One	Two	-5.804	3.534	0.864	-18.427	6.819
	Three	-29.571*	4.772	0	-46.614	-12.528
	XOR	-56.464*	8.783	0	-87.831	-25.097
	AND	-91.429*	15.778	0.001	-147.779	-35.078
	OR	-64.214*	15.126	0.014	-118.235	-10.194
Two	One	5.804	3.534	0.864	-6.819	18.427
	Three	-23.768*	4.703	0.003	-40.564	-6.972
	XOR	-50.661*	8.898	0.001	-82.437	-18.884
	AND	-85.625*	15.801	0.002	-142.058	-29.192
	OR	-58.411*	15.434	0.034	-113.531	-3.29
Three	One	29.571*	4.772	0	12.528	46.614
	Two	23.768*	4.703	0.003	6.972	40.564
	XOR	-26.893	9.297	0.173	-60.096	6.31
	AND	-61.857*	15.672	0.025	-117.828	-5.886
	OR	-34.643	15.362	0.475	-89.506	20.22
XOR	One	56.464*	8.783	0	25.097	87.831
	Two	50.661*	8.898	0.001	18.884	82.437
	Three	26.893	9.297	0.173	-6.31	60.096
	AND	-34.964	16.512	0.566	-93.934	24.005
	OR	-7.75	20.483	1	-80.902	65.402
AND	One	91.429*	15.778	0.001	35.078	147.779
	Two	85.625*	15.801	0.002	29.192	142.058
	Three	61.857*	15.672	0.025	5.886	117.828
	XOR	34.964	16.512	0.566	-24.005	93.934
	OR	27.214	18.735	0.939	-39.695	94.123
OR	One	64.214*	15.126	0.014	10.194	118.235
	Two	58.411*	15.434	0.034	3.29	113.531
	Three	34.643	15.362	0.475	-20.22	89.506
	XOR	7.75	20.483	1	-65.402	80.902
	AND	-27.214	18.735	0.939	-94.123	39.695

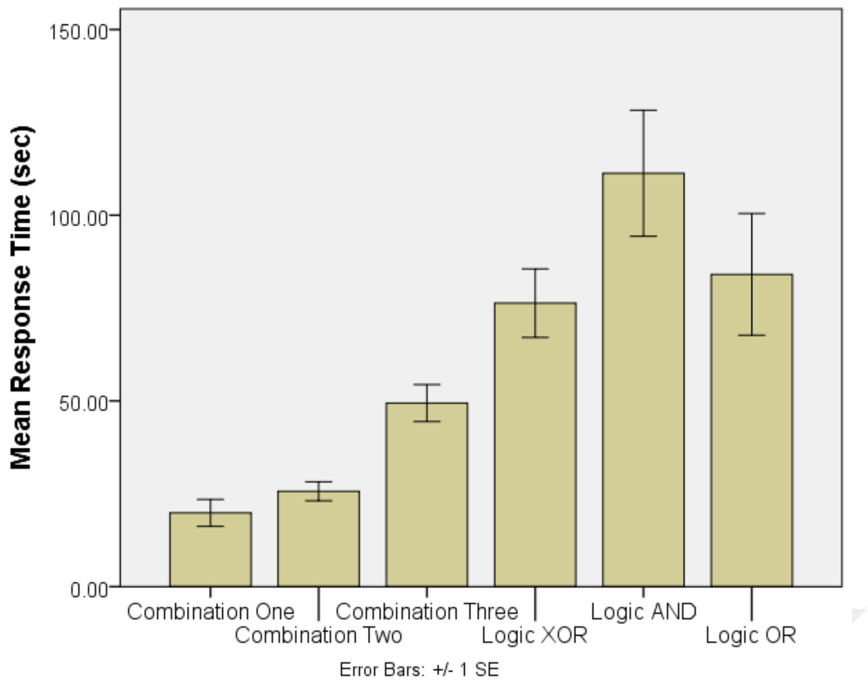


Figure 4.2: Percentage of mean response time according to questions types.

4.1.3 Gaze Coherence

During the experiment partners attempted a total of 16 puzzles, 12 of which required them to coordinate their gaze (i.e. two partners need to dwell on the same cell to reveal the shape in that cell), whereas in 4 conditions the puzzles were completely open (i.e. no forced gaze coordination). Trials, which requires gaze coordination are called *Closed* trials, remaining trials are called *Open* trials.

We first tested whether the 14 pairs in our sample could achieve a significant level of gaze coherence during the tasks, since the success of the experiment depends on the performance of the partners for dwelling on the same cells at the same time to be able to solve the puzzles. For this purpose, we computed the average gaze coherence value obtained during all puzzle blocks for each pair, and then performed a one-sample t-test to observe if the mean gaze coherence differs from 0 (i.e. no coherence). The result indicated that the gaze coherence was significantly larger than 0 on average, $t(13)=27.74$, $p<.001$. We then contrasted the gaze coherence values observed during tasks that required participants to coordinate their gaze over the cells (i.e. the closed condition) with those tasks they were free to view the entire puzzle (i.e. the open condition). Overall comparison of gaze coherences can be seen in Figure 4.3.The dependent t-test results indicated that the gaze coherence in the closed condition is significantly higher than the open condition (Mean Difference=-.17, $t(13)=-6.79$, $p<.001$).

Finally, we checked whether gaze coherence values differed across each puzzle type. A dependent t-test comparing the mean gaze coherence values of combination and logic puzzles suggested that there is marginally higher gaze coherence during the combination type trials, $t(13)=2.08$, $p=.058$. Moreover, a repeated measures ANOVA was conducted over all 6 puzzle types to check for puzzle specific differences. Although the partners struggled more while attempting the logic type puzzles, their gaze coherence levels were not significantly different among the 6 puzzle types, $F(5,65)=1.49$, $p>.05$ average question values of each question type can be seen in Figure 4.4.

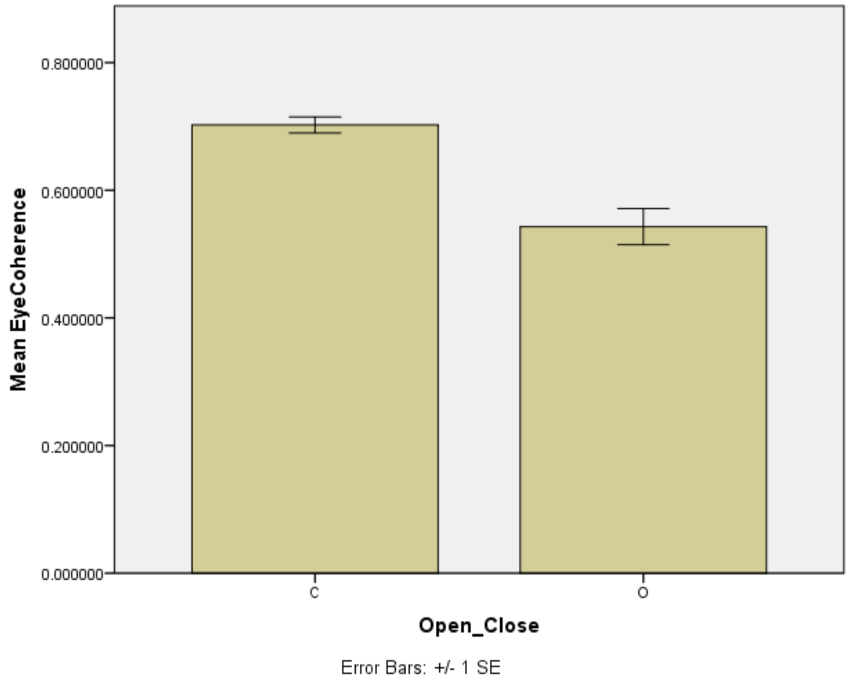


Figure 4.3: Mean gaze coherences in Open and Closed condition

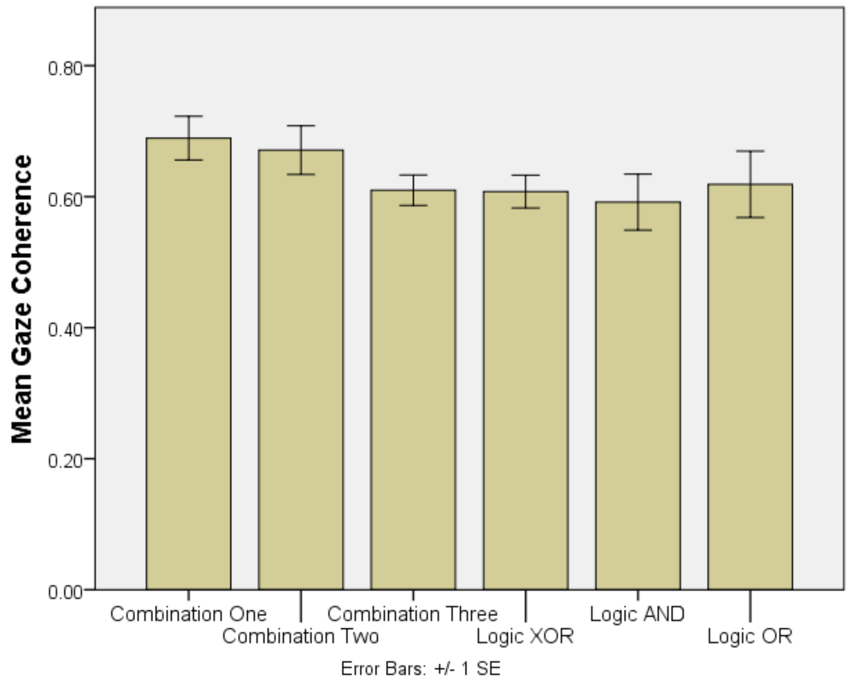


Figure 4.4: The mean gaze coherence values observed during each puzzle type

4.2 Oxygenation Analysis Results

In this analysis we focused on whether different problem types differed in terms of the oxygenation trends they elicited in the prefrontal cortices of the participants. For this purpose, first the raw NIR signals were low pass filtered to attenuate effects due to heart beat and respiration. Optodes that were saturated due to poor skin contact or excessive motion were excluded from the analysis. Finally, Modified Beer Lambert law (MBLL) was applied to convert raw NIR signals into oxy-hemoglobin (HbO) and deoxy-hemoglobin (HbR) signals. The first 5 seconds of each block was considered as the baseline during the MBLL computation. Since 14 pairs participated in the experiment, we analyzed brain responses obtained from 28 participants for the oxygenation analysis. We first focused on the distinction between logic type puzzles with combination type puzzles. Overall, logic puzzles elicited a stronger HbO response as compared to the combination type puzzles, which indicates that the logic puzzles required more neural resources particularly at optode 3, $t(27)=-2.67$, $p<.05$, optode 7, $t(27)=-2.60$, $p<.05$, optode 9, $t(27)=-2.19$, $p<.05$, and optode 11, $t(26)=-2.21$, $p<.05$. The t-map superimposed over the prefrontal cortex summarizes the most significant differences for the logic vs combination comparison.

The increased oxygenation in the left dlPFC around optode 3 is possibly due to the increased difficulty involved with finding the rule implied in the shapes for the logic type puzzles. Participants also spent more time in logic puzzles, which may have forced them into a more collaborative mode of thinking to overcome the challenge. Increased activity observed in the fronto-polar regions around optodes 7 and 9, which are implicated in theory of mind studies, could be due to this pressing need for collaboration. Optode 11 is also a similar side that tends to respond when there is a need for coordinating joint action (Cui et al., 2012).

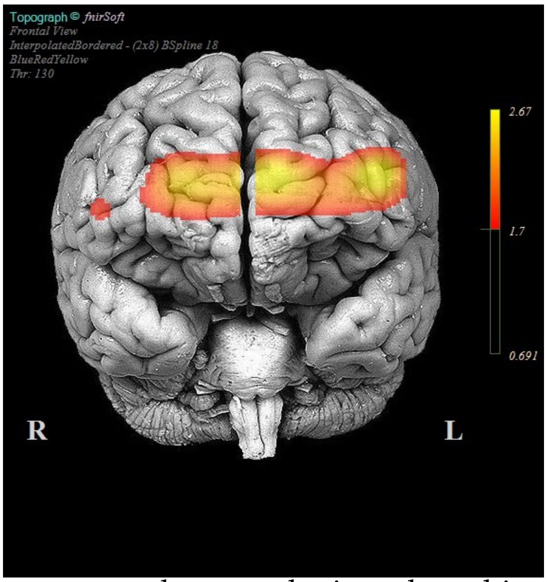


Figure 4.5: The t-map contrast between logic and combination puzzles superimposed over the prefrontal cortex.

We also considered differences among specific puzzle types via one-way repeated measures ANOVA analysis. The mean HbO levels observed during each puzzle type is presented in Figure 4.6. The results indicated a linearly increasing HbO trend at each optode from combination one, two, three to logic XOR, OR, AND puzzle types. The logic-AND type elicited the strongest HbO response. The difference was most significant at optode 1, $F(2.82, 73.46)=3.83$, $p<.05$, partial $\eta^2=.13$, optode 3, $F(3.01, 78.30)=6.51$, $p<.01$, partial $\eta^2=.20$, optode 4, $F(3.09, 80.34)=5.62$, $p<.01$, partial $\eta^2=.18$, optode 5, $F(2.94, 76.39)=4.18$, $p<.01$, partial $\eta^2=.14$, optode 6, $F(3.06, 79.61)=4.97$, $p<.01$, partial $\eta^2=.16$, optode 7, $F(3.00, 78.05)=4.40$, $p<.01$, partial $\eta^2=.15$, optode 11, $F(3.12, 78.09)=3.15$, $p<.05$, partial $\eta^2=.11$, optode 12, $F(3.14, 78.40)=3.83$, $p<.05$, partial $\eta^2=.13$, optode 14, $F(3.08, 80.16)=3.08$, $p<.05$, partial $\eta^2=.11$, optode 16, $F(3.14, 81.70)=3.83$, $p<.05$, partial $\eta^2=.10$. The t-map contrast between logic and combination puzzles can be seen in the Figure 4.5 as superimposed over the prefrontal cortex.

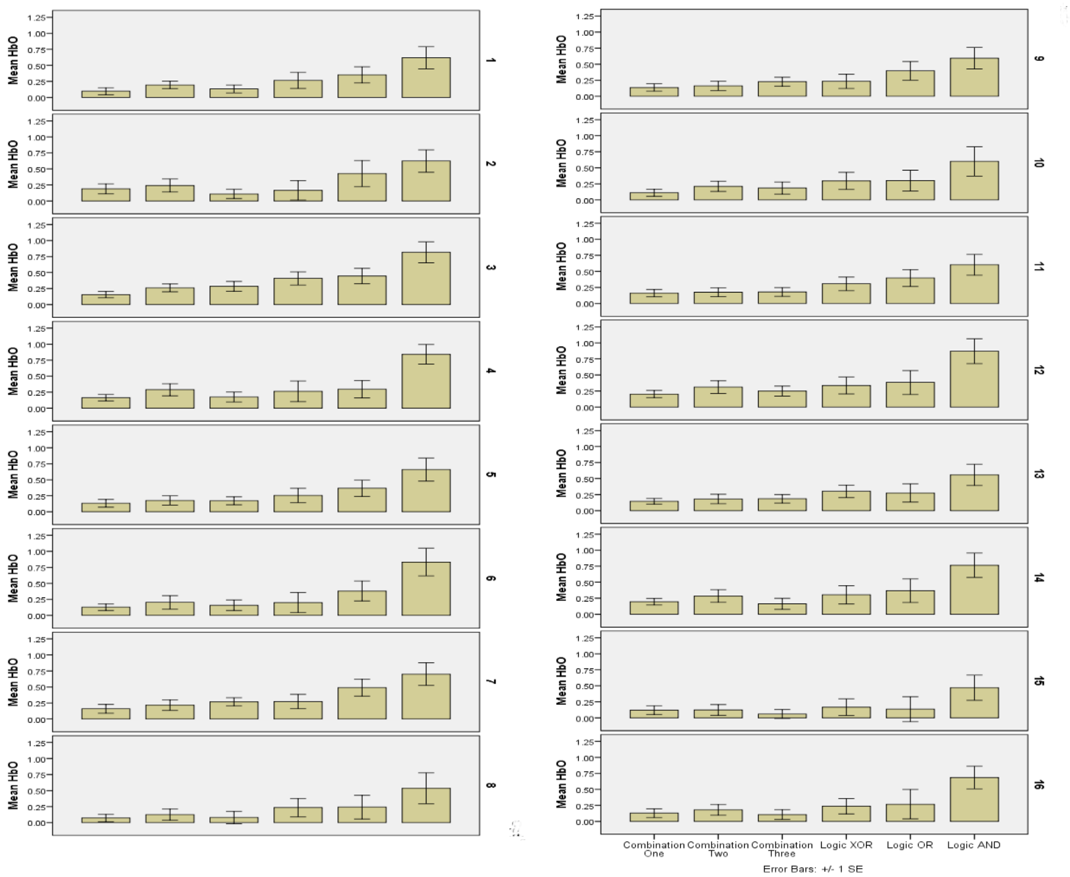
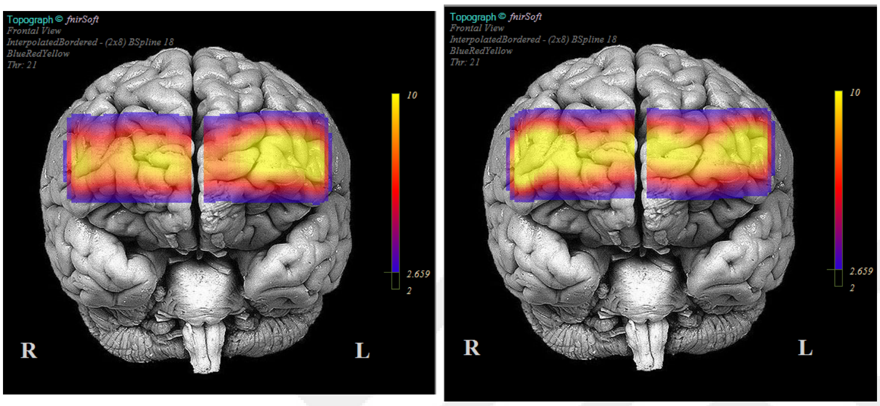


Figure 4.6: Mean HbO values observed during each puzzle type at 16 optodes.

4.3 Brain-to-Brain Coherence Analysis Results

The coherence between fNIRS signals and eye movements of both partners during the experiment was computed by employing a wavelet transform coherence analysis. First of all, we performed one-sample t-tests over mean HbO coherence increase and mean HbR coherence increase values to observe at which optodes coherence increase was non-zero. Figure 4.7 below shows the t-maps superimposed over the PFC with B-spline interpolation computed with the fNIR Soft software. The t-maps are thresholded at the significance level of α=0.01, which correspond to a t-value of 2.65. Both maps showed highly significant difference from 0-coherence, which was particularly strong at left and right dlPFC, left dmPFC and fronto-polar cortices. Overall, this suggests that while the participants were engaged with our task, significant levels of brain-to-brain coherence was observed among them, both with respect to HbR and HbO coherence increase measurements.



(a) HbO (b) HbR

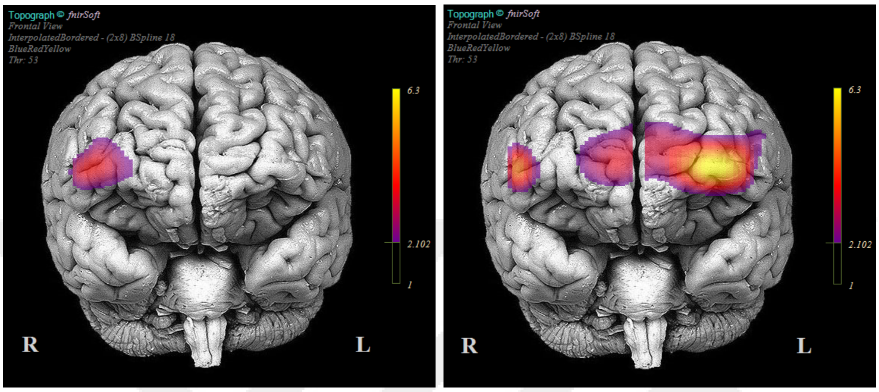
Figure 4.7: The contrast t−maps for the mean HbO coherence increase (left) and mean HbR coherence increase (right) signals averaged over all tasks

This general analysis is followed up with more fine grained distinctions based on the design of the experiment. In particular, we contrasted eyes open\closed and puzzle type categories to observe if brain to brain coherence is modulated by forced gaze coordination as well as puzzle type. The results of each analysis is summarized in the following subsections.

4.3.1 Eyes Open vs Closed

During the experiment partners attempted a total of 16 puzzles, 12 of which required them to coordinate their gaze (i.e. two partners need to dwell on the same cell to reveal the shape in that cell), whereas in 4 conditions the puzzles were completely open (i.e. no forced gaze coordination). We tested whether this change made any significant difference on the mean coherence and mean coherence increase values between the partners. Firstly, we compared the mean HbO coherence values for the eyes open and eyes closed blocks via paired t-tests. A significantly higher coherence was observed for the eyes closed blocks in optode 14, $t(13)=-3.46, p<.01$ and optode 16, $t(13)=-3.04, p<.05$ only, which are located over the right dorsolateral PFC.

When we focused on the mean coherence increase in HbO between eyes open and closed blocks, we observed stronger differences. In this case the t-tests were conducted after the mean HbO coherence values were corrected by subtracting the HbO coherence observed during rest periods. The results showed that significantly larger mean coherence values are obtained during the eyes closed trials at optode 4, t(13)=-5.01, p<.001, optode 6, t(13)=-6.16, p<.001, optode 7, t(13)=-2.88, p<.05, optode 8, t(13)=-2.76, p<.05, optode 9, t(13)=-2.4, p<.05, optode 10, t(13)=-3.29, p<.01, optode 16, t(13)=-1.11, p<.001. The difference was marginally significant at optodes 1, 3, 5 and 14 (i.e. p<.06 in all cases). A b-spline interpolated t-map superimposed over the prefrontal cortex summarizes the most significant differences for the eyes open vs closed comparison.

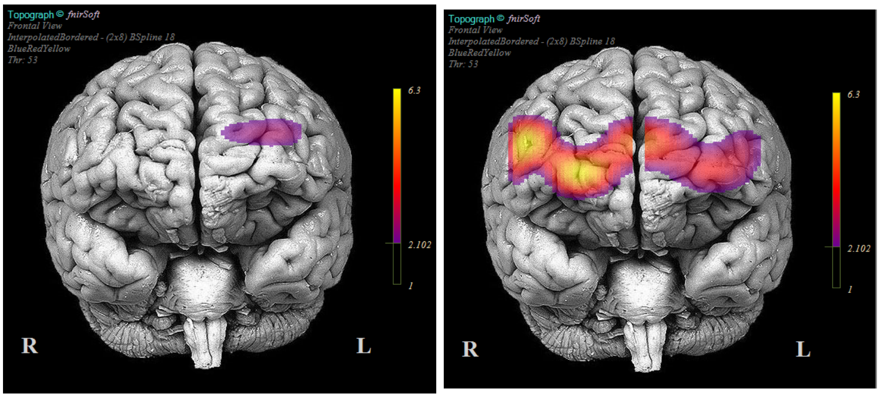


(a) Block coherence (b) Coherence increase

Figure 4.8: The contrast t-maps for the mean HbO coherence (left) and mean HbO coherence increase (right) signals observed during eyes open and eyes closed blocks superimposed over the prefrontal cortex.

A similar coherence analysis applied over HbR signals also indicated a similar difference between eyes open vs closed conditions. First of all, we contrasted the mean HbR coherence values obtained for eyes open and closed conditions. The dependent t-tests indicated that there is significantly higher HbR coherence at optode 3, t(13)=-2.26, p<.05 and optode 5, t(13)=-2.67, p<.05, during the eyes closed case as compared to the eyes open case. These optodes fall over the left dlPFC and left dmPFC regions. We also compared eyes open and closed blocks in terms of the mean coherence increase in HbR during those blocks. Similar to the HbO analysis, we observed that the difference between eyes open and eyes closed cases is much stronger after baseline correction, particularly at optodes in the right prefrontal cortex. The strongest contrasts were observed at optode 3, t(13)=-2.56, p<.05, optode 4, t(13)=-2.89, p<.05, optode 6, t(13)=-3.46, p<.01, optode 9, t(13)=-3.88, p<.01, optode 10, t(13)=-2.88, p<.05, optode 12, t(13)=-6.23, p<.015, optode 13, t(13)=-5.10, p<.001, optode 14, t(13)=-2.24, p<.05, optode 15, t(13)=-5.20, p<.001 and optode 16, t(13)=-3.18, p<.001.

The main rationale for including an eyes open condition was to provide a control case where partners were free to dwell over any cell they wish to solve the puzzle. From the analysis of eye tracking data, we observed that participants tended to exhibit significant gaze coherence even though the gaze togetherness constrained was removed. This seems to suggest that the participants were primed to scan the puzzle as if they were doing it in the



(a) Block coherence (b) Coherence increase

Figure 4.9: The contrast t-maps for the mean HbR coherence (left) and mean HbR coherence increase (right) signals observed during eyes open and eyes closed blocks superimposed over the prefrontal cortex.

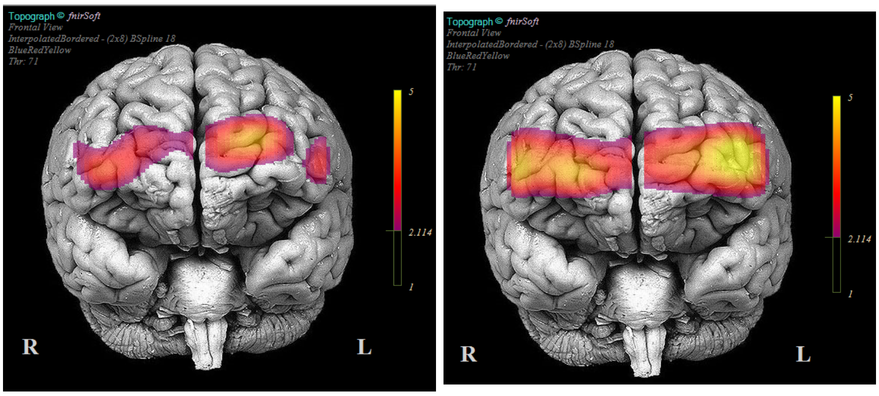
eyes closed condition. However, our results for the mean coherence increase in HbO and HbR signals suggest that the eyes closed condition elicits more brain-to-brain coherence, possibly due to the way the eyes closed condition forces partners to view the problem space in a coordinated manner.

4.3.2 Logic vs Combination Puzzle Types

Next we investigated whether the type of the problem had any effect on the brain-to-brain coherence measures. Similar to the eyes open/closed analysis, we contrasted logic and combination puzzle types in terms of the mean HbO and HbR coherence and coherence-increase values via dependent t-tests. We observed that logic questions overall elicited significantly higher mean HbO coherence and mean HbO coherence increase values (Figure 4.10). In the mean coherence case, the most significant brain-to-brain coherence is observed in the left dmPFC and bilateral dlPFC regions, whereas in the mean coherence increase case brain-to-brain coherence difference is significant in a larger number of optodes covering mostly the bilateral dlPFC and dmPFC.

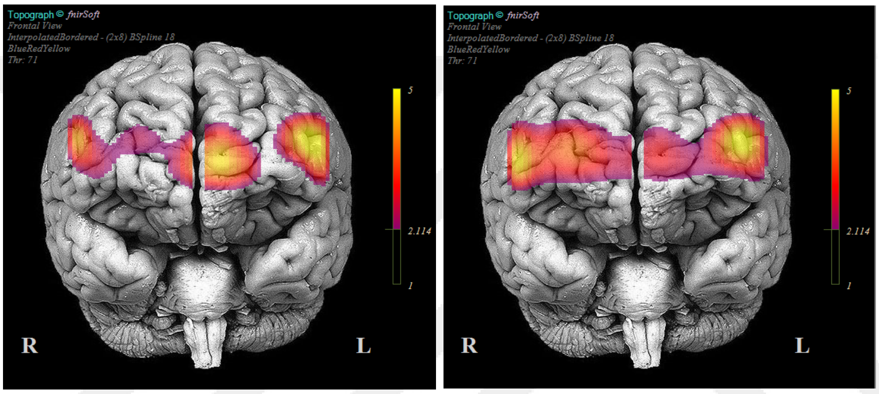
Similarly, we observed that logic questions elicited significantly higher mean HbR coherence and mean HbR coherence increase values (Figure 4.11). In the mean coherence case, the most significant brain-to-brain coherence is observed in the left dmPFC and bilateral dlPFC regions, whereas in the mean coherence increase case brain-to-brain coherence difference is significant in a larger number of optodes covering mostly the bilateral dlPFC and dmPFC.

We also considered differences among specific puzzle types in terms of their mean HbO and HbR coherence increase values via one-way repeated measures ANOVA analysis. The mean HbO coherence increase levels observed during each puzzle type is presented in Figure 4.12. The results indicated that higher levels of mean HbO coherence increase occurred during combination three and the logic puzzle types. The logic-AND type elicited the strongest HbO coherence increase response. The difference was most significant at optode 1, $F(3.23, 42.00)=2.42$, $p<.05$, partial $\eta^2=.16$, optode



(a) Block coherence (b) Coherence increase

Figure 4.10: The contrast t-maps for the mean HbO coherence (left) and mean HbO coherence increase (right) signals observed during the logic and combination puzzle types.



(a) Block coherence (b) Coherence increase

Figure 4.11: The contrast t-maps for the mean HbR coherence (left) and mean HbR coherence increase (right) signals observed during the logic and combination puzzle types.

3, F(2.69, 35.00)=4.89, p<.01, partial η^2=.27, optode 4, F(2.95, 38.38)=3.27, p<.05, partial η^2=.20, optode 6, F(2.55, 33.08)=2.89, p<.05, partial η^2=.18, optode 12, F(2.38, 30.97)=4.67, p<.05, partial η^2=.22, and optode 13, F(2.70, 34.93)=4.67, p<.01, partial η^2=.26.

The mean HbR coherence increase levels observed during each puzzle type is presented in Figure 4.13. The results indicated that higher levels of mean HbR coherence increase occurred during combination three and the logic puzzle types. The logic-AND type elicited the strongest HbR coherence increase response. The difference was most significant at optode 1, F(2.68, 42.00)=2.91, p<.05, partial η^2=.18, optode 11, F(2.33, 27.99)=3.48, p<.05, partial η^2=.23, optode 12, F(2.11, 27.46)=3.06, p<.05, partial η^2=.19, optode 13, F(2.18, 28.38)=3.89, p<.05, partial η^2=.23, and optode 15, F(2.81, 36.51)=4.92, p<.05, partial η^2=.27.

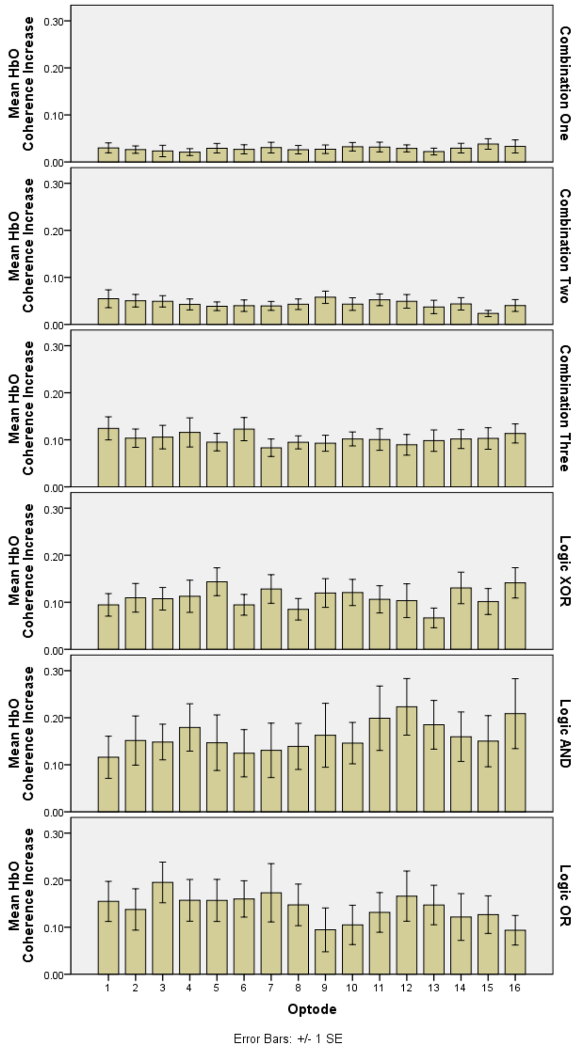


Figure 4.12: The mean HbO coherence increase levels observed during each puzzle type.

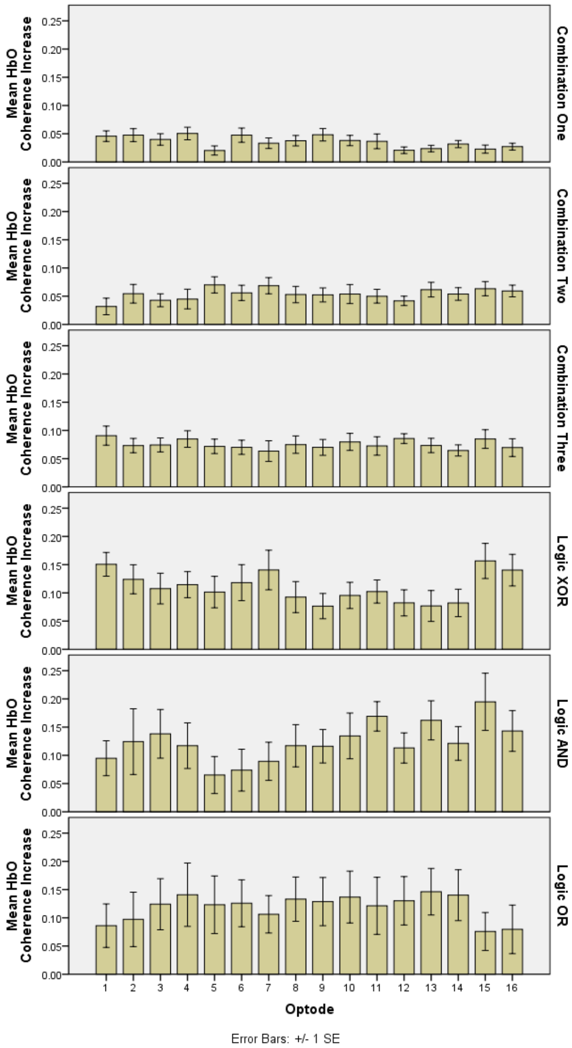


Figure 4.13: The mean HbR coherence increase levels observed during each puzzle type.

CHAPTER 5

DISCUSSION AND CONCLUSION

In this chapter, the results of Joint Fluid Intelligence experiment are discussed. The chapter is organized under three main parts. These parts are discussion of behavioral results, discussion of neural activation results, and discussion of neural coherence results respectively.

5.1 Discussion of Behavioral Results

Behavioral results of joint fluid intelligence experiment are discussed in this part. For behavioral analysis, we analyzed eye coherence, response time, and correctness of the responses. The independent variables were requirement for gaze togetherness and question type. We analyzed question types in two different levels. At the first level we distinguished 2 broad types of puzzles, namely combination and logic puzzles. At the second level we distinguished 3 levels for combination puzzles and 3 different question types for logic puzzles.

5.1.1 Accuracy

In the analysis of accuracy in joint fluid intelligence task, we found that participants performed nearly perfect in combination questions. Performance in logic questions have more variability. Pairs answered 94.6% (N=14, SD=7.7) of combination questions correctly whereas they answered 60% (N=14, SD=23.4) of logic questions correctly. These results are consistent with the behavioral results of Prabhakaran et al. (1997) and norming results in Matzen et al. (2010). Variability in difficulty is an important factor because we hypothesised that chance of observing increased neural coherence would increase as the difficulty increases. Results of accuracy values across question types shows that questions introduced variability in terms of difficulty. Therefore, we can use these question types to investigate the effect of problem difficulty on the neural and behavioral coherence.

5.1.2 Duration

In the analysis of accuracy in joint fluid intelligence task, we found that logic questions took significantly longer time two answer. It is expected that questions that are more difficult require more time to answer. We should also note that, there was a time limit of 3 minutes in each trial and several logic trials are ended with timeout. Pairwise comparison of question types with respect response time showed that level-1 and level-2 combination questions took significantly short time to answer. Level-3 questions took significantly longer than level-1 and level-2 question and significantly shorter than logic AND questions. There was no significant difference among XOR, OR, and Level-3 questions. This shows that level-3 questions, although in combination category, falls between combination and logic category. There was no significant difference among logic question types in terms of response time. We observed that participants perform their first scan on the question relatively easily. Most pairs scanned all fragments of a question in sequential order. We call this as first scan (or first iteration). Most 1-level and 2-level questions can be solved in first iteration. As the participants can maintain their behavioral coordination more easily in first iteration, questions which need 1 or 2 iterations can be answered very quickly. However, 3-level questions, and especially logic questions, requires revisiting previous fragments. Maintaining behavioral coordination is more difficult in these questions because participants had to actively decide and cooperate on which fragment they need to revisit. Therefore, in closed conditions, difficulty of question increases the difficulty of maintaining behavioral coordination. Since maintaining coordination is mandatory to solve closed problems, closed condition affects difficult problems more strongly. To sum up, we found that type of problems significantly effects response time. Pairwise comparison of question types are in line with accuracy values. Through that, we can argue that we introduced sufficient variability in terms of difficulty to investigate effect of difficulty on neural and behavioral coherence.

5.1.3 Eye Coherence

In the analysis of gaze coherence in joint fluid intelligence task, we calculated participants gaze coordination by using WTC. We analyzed these coherence values with respect to open vs closed conditions and question types. We found that during closed trials there was significantly high gaze coherence compared to open trials. These results are in line with our expectation, as maintaining gaze coordination is mandatory in closed trials and optional in open trials. Gaze coherence was significantly higher than 0 on average in all conditions. Comparison of logic and combination trials yielded marginally significant results with gaze coherence is being higher during the combination trials. As shown in response time analysis, logic question took longer to solve. Therefore, we can argue that the gaze coherence difference between logic and combination trials are due to the duration of the trials. Furthermore, comparison of eye coherence values across the question types did not show any significant differences among them. This shows the marginal significance we found in general trial types is not supported by fine grained analysis of question types. Overall, analysis of eye coherence results yielded necessary evidence for us to argue that by making questions individually accessible we incited behavioral coordination between participants. However,we observed that the difficulty of the problem did not have a significant effect on the degree of behavioral coherence observed among the partners.

5.2 Discussion of Neural Activation Analysis Results

Results of neural activation analysis is discussed in this part. In behavioral analysis, it is shown that logic questions took longer to respond and have lower correctness rate. In neural activation analysis, we found that logic puzzles elicited stronger HbO response compared to the combination puzzles. This increased neural activity is significantly stronger at optode 3, optode 7, optode 9, and optode 11.

In Prabhakaran et al. (1997), they found that combination problems (named by them as figural problems), activated right frontal and bilateral parietal regions. Furthermore, they found that while logic problems more strongly activated same areas with figural problems, they additionally activated areas involved in working memory and associative and executive processes. Optode 3 is close to the left dlPFC. Left dlPFC is associated with manipulation of information in working memory (Barbey, Koenigs, & Grafman, 2013; Smith, Jonides, & Koeppe, 1996). Findings in optode 3 is consisted with these findings. Findings in optode 11 is similar to the finding in Cui et al. (2012). Bilateral activation observed in mPFC (optodes 7,9,11) can be interpreted with respect to the task's relationship with Theory of Mind(ToM) (Saxe & Powell, 2006). It is expected that logic puzzles required more coordination, because, as behavioral data suggests, they are more difficult. Response time, as a product of difficulty, can result in a situation which participants are required to maintain their coherences for a longer period of time. However, we did not find any difference in open vs closed conditions in neural activation analysis. It is consistent with the accuracy and response time analysis. The effect of open and closed conditions on eye coherence analysis is not reflected by the neural activation analysis. This may be due to the fact that participants are allowed to engage in a dialogue during both open and closed questions. We also analyzed neural activation values with respect to 6 question types. We found a linearly increasing trend at each optode from levels 1-2-3 to logic XOR, OR, AND puzzle types. This trend is consistent with accuracy and response time values. The logic AND questions elicited the strongest HbO response. We found significantly higher activation in most of the optodes with a left lateralization. This activation pattern and lateralization is consistent with the findings of Prabhakaran et al. (1997) and Haier et al. (1988).

5.3 Discussion of Brain-to-Brain Coherence Analysis Results

Results of brain-to-brain coherence analyses discussed in this part.

We analyzed, both overall mean HbO and HbR coherence increase values to find the optodes with non-zero coherence increase. Both HbO and HbR values showed significant non-zero coherence increase. This effect is particularly strong in left, right dlPFC and left dmPFC and fronto-polar cortices. These results show during Joint Intelligence Task, significant brain-to-brain coherence were observed among participants in HbR and HbO signals. For more detailed analysis, we analyze coherence and coherence values with respect to open/close condition and question types.

5.3.1 Open vs Closed Condition

We expected to find increased coherence during the closed condition compared to the open condition, because it was necessary for the participants to coordinate the eye gaze to complete the closed questions. Indeed, we find significantly higher coherence in optodes 14 and 16, which are located over the right dlPFC. This coherence pattern in line with Cui et al. (2012). This mutual activation can be related to need for regulating and planning eye-movements in order to maintain behavioral coordination (Pierrot-Deseilligny, Müri, Nyffeler, & Milea, 2005; Pochon et al., 2001).

Analysis of mean coherence increase values yielded stronger differences. According to results on baseline corrected HbO coherence increase values, in optode 4, 6, 7, 8, 9, 10, and 16 there were significantly higher coherence increases during closed condition compared to open condition. The difference in optodes 1, 3, 5, and 14 was marginally significant ($p<.06$). Bilateral coherence increase in dmPFC can be interpreted with the social aspect of the task. Findings in dmPFC during and right dlPFC forced cooperation is consistent with findings in Liu et al. (2016). With the inclusion of marginally significant optodes, these coherence patterns are strengthened and show slight left lateralization.

Analysis of HbR coherence yielded similar results in symmetrical regions, which we found coherent in HbO analysis. In HbR coherence analysis, we found coherence significantly higher coherence in areas close to left dlPFC and left vmPFC. We can argue that the coherence in left dlPFC is due to the need of coordinately planning and executing eye movements. Coherence in the vmPFC can be associated with the social interaction and ToM. Similar to the HbO analysis, coherence increase analysis yielded broader coherence pattern. We found increased coherence in most of the optodes with stronger coherence increase in right side. This coherence patterns are symmetrical to the patterns in HbO analysis.

5.3.2 Logic vs Combination Puzzle Types

In the analysis of coherence values with respect to puzzle types, we found that logic questions elicited higher coherence, and coherence increase values. In the mean HbO coherence analysis, we found coherence is stronger in left dmPFC and bilateral dlPFC. This left lateralization in logic questions is consistent with the results of Prabhakaran et al. (1997). Considering the response times of logic questions are significantly higher and there is no significant difference between eye coherence values with respect to question type, we can argue that the participants maintained their behavioral coordination even though the task duration is significantly longer. In the coherence increase analysis, we found increased coherence in most of the frontal cortex. Furthermore, when we analyzed coherence values with respect to question types, we found logic AND questions elicited the strongest coherence increase. It means that results of coherence increase analysis is consisted with the duration and accuracy analysis. Results of HbO coherence and HbO coherence increase analyses are consistent with the behavioral analyses. In mean HbR coherence analysis, we found similar results with HbO analysis. In HbR analysis coherences in dlPFC was stronger. Results of HbR coherence increase analysis is also similar to the HbO coherence increase analysis with coherence increases being slightly lower. Since in coherence increase analysis rest coherence values are subtracted from block coherence values we found increased coherence in nearly all optodes even if the block coherence values are not significantly higher. We should note that coherence between two fNIRS signal does not mean that there is activation in the optode we analyzed; signals can be coherent while not presenting significant activation.

5.4 Conclusion

In this study, we investigated brain-to-brain coherence patterns among collaborating partners during a joint fluid intelligence task. For this purpose, we created a joint version of Sandia matrices fluid intelligence task. We simultaneously recorded participants' frontal cortices by a dual fNIRS setup. Behavioral results measured as response time, correctness of answers and eye coherence values during the task. We found that the question types have a significant effect on response time and accuracy. We can conclude that question types are successful in terms of introducing the necessary level of difficulty to the task to explore factors that influence brain-to-brain coherence patterns. We also found by making gaze coordination mandatory we significantly manipulated gaze coherence during the tasks. Therefore, we can argue that we successfully forced participants to coordinate at the behavioral level. Neuroimaging results are analyzed in terms of activation and coherence. We found that significantly higher activation in bilateral dmPFC, right vmPFC, and left dlPFC during logic type trials. These regions are associated with social interaction and theory of mind. We did not find significant relation between open/closed condition and neural activation. However, from behavioral analyses we can infer that even though logic trials are significantly longer participants were able to maintain similar eye coherence values during these trials. From there we can argue that logic trials incited stronger type of joint action hence the stronger activation of the regions, which associated with joint action, and theory of mind. We can interpret the activation in the dlPFC with the association of difficulty of the task and working memory. Form open/closed condition analyses, we can argue that forcing participants to cooperate by making questions individually inaccessible, resulted in increased coherence in both behavioral and neural level. In the coherence analyses, we found stronger coherence in right dlPFC (HbO), left vmPFC (HbR), and left dlPFC (HbR), higher coherence in these areas can be interpreted as the tasks relation with planning and executing eye movements. When we analyzed coherence increase during open/close condition, we found increased coherence during closed trials in almost all optodes. These coherence patterns were slightly left lateralized in HbO and slightly right lateralized in HbR. Analyses of coherence values with respect to puzzle types showed that logic puzzles elicited significantly higher coherence values. We found higher mean coherence values in bilateral dmPFC and bilateral dlPFC, from these results we can argue that difficulty of the puzzle enhances the coherence, which we found in open/close analysis. Furthermore, detailed comparison of question types showed that logic AND questions elicited highest coherence and coherence increase values. Since stronger neural coherence does not necessarily means the stronger neural activation, it is expected that we found broader coherence patterns compared to activation patterns. However, activation patterns are arguably better indicator to determine task difficulty and joint effort because it distinguishes activated areas during the joint fluid intelligence task. With the combination of behavioral and neural results, we can argue that difficulty of the question significantly effects the neural activation and neural coherence between participants.

Findings in this study regarding the behavioral and neural coherence between people during joint fluid intelligence task have important findings regarding the joint action and hyperscanning literature. We found increased neural activation in brain areas related to the fluid intelligence and joint action. We also find that forcing people to cooperate in a fluid intelligence task increases behavioral and neural coherence between them. Spatial localization of the coherent brain areas are consistent with both joint action and fluid intelligence literature. Furthermore, we found that the difficulty of the joint task enhances the neural coherence between people. These finding implies that jointly solving a problem causes a degree of neural synchrony among people and the degree of synchrony increases with the difficulty of the problem.

5.5 Limitations and Future Directions

This study had limitations in terms of experiment methods and materials. We imaged pair's frontal cortices during a joint fluid intelligence task. The area, which we could image, is limited. Both joint action and fluid intelligence literature has findings which spans outside the frontal cortex. Imaging more regions simultaneously can lead to a more detailed map of relations between participants during joint problem solving. Furthermore, using a neuroimaging device limits the overall duration of the experiment. Since we found a gradual increase in question types, time limitation can be circumvented by refining 6 question types in 2 puzzle types to one question for each puzzle type. This could allow us to concentrate on the different condition to manipulate the strength of interaction. Another limitation regarding the fluid intelligence tasks is the difficulty to fix the duration of a block. Since our block did not have a fixed duration, we selected our task cycle in WTC according to shortest blocks. Although, we used the response time as a variable to measure difficulty of the questions, it would be better for the analysis to have a fixed block length.

In future studies, more natural forms of joint problem solving can be investigated. In this study participants had to cooperate in order to access the problem, however once accessed the problem is individually solvable. We artificially converted the problem to a joint problem. Since the problem is individually solvable, we could not measure the contribution of each participant to the joint task. A paradigm, which includes naturally joint problems, can be helpful in investigating neural and behavioral correlates of joint problem solving. Another possible line of research would be the investigation of offline execution of jointly planned action. It would present us with the opportunity to investigate joint action in the absence of interaction medium. Since humans can execute joint actions even if the interaction medium is disrupted, this line of work can reveal more about the correlates of joint action. In conclusion, hyperscanning during joint actions in a variety of social interaction domains is a relatively new and developing line of research in neuroscience. Future studies with hyperscanning can reveal more about types of social interactions and social interaction mediums.

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