Learning Joint Actions in Human-Human Interactions

by

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ABSTRACT

Understanding human-human interactions during the performance of joint motor tasks is critical for developing rehabilitation robots that could aid therapists in providing effective treatments for motor problems. However, there is a lack of understanding of strategies (cooperative or competitive) adopted by humans when interacting with other individuals. Previous studies have investigated the cues (auditory, visual and haptic) that support these interactions but understanding how these unconscious interactions happen even without those cues is yet to be explained. To address this issue, in this study, a paradigm that tests the parallel efforts of pairs of individuals (dyads) to complete a jointly performed virtual reaching task, without any auditory or visual information exchange was employed. Motion was tracked with a NDI OptoTrak 3D motion tracking system that captured each subject's movement kinematics, through which we could measure the level of synchronization between two subjects in space and time. For the spatial analyses, the movement amplitudes and direction errors at peak velocities and at endpoints were analyzed. Significant differences in the movement amplitudes were found for subjects in 4 out of 6 dyads which were expected due to the lack of feedback between the subjects. Interestingly, subjects in this study also planned their movements in different directions in order to counteract the visuomotor rotation offered in the test blocks, which suggests the difference in strategies for the subjects in each dyad. Also, the level of de-adaptation in the control blocks in which no visuomotor rotation was offered to the subjects was measured. To further validate the results obtained through spatial analyses, a temporal analyses was done in which the movement times for the two subjects were compared. With the help of

these results, numerous interaction scenarios that are possible in the human joint actions in

without feedback were analyzed.

# DEDICATION

I dedicate my work to my beloved parents, Mrs. And Mr. R.C.Agrawal.

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CHAPTER 1

INTRODUCTION

## 1.1 WHAT ARE JOINT ACTIONS?

Joint actions involve two or more agents coordinating their behavior in space and time to perform a particular task (Buneo et al. 2014). Joint actions form a part of our daily lives, for example, clinking of glasses by two people, playing a tennis game or even two pianists playing a piano duet. Although different species have their own mechanism of engaging in social behavior, the ability to share psychological states in most developed in humans. This ability enables humans to engage in complex collaborative activities which other species are not capable of doing. Research has shown that in order for the communication to exist between individuals, joint actions in humans are necessary. We start participating in joint actions from the very beginning of our lives. Infants follow the gaze of adults and learn to imitate their actions using shared attention. These cognitive capacities then develop and contribute to the development of higher level mechanisms such as Theory of Mind, through which we learn to infer the mental state of others (Baron-Cohen 1995).

Although, the day-to-day social activities such as walking alongside a person with the same rhythm might seem to be trivial at first, understanding the complex cognitive and neural processes behind such a process is quite challenging. As Allport studied around 90 years ago (Allport 1924), even simple joint actions such as carrying a heavy object together are challenging in that the two individual bodies and mind must be coordinated. Wolpert and colleagues outlined the importance of motor system in social interactions. The parallel processes underlying motor control and social

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interaction are very complex as the computation of motor state involves a larger number of complex parameters. A bigger problem occurs when the motor system has to deal with the responses from multiple people. The time delays and non-linear relation between our actions and the multiple responses to it by different people makes social interaction difficult (Wolpert et al. 2003).

Most of what we know about joint actions has been derived from the studies in social interactions which includes how two individuals coordinate by inferring the mental states and actions of each other. This concept is called 'co-representation'. Studies on co-representation have shown a strong tendency in individuals to monitor the actions of their partners leading to a "motor contagion", a phenomenon in which the observer's motor system might replicate some features of the stimulus received from the actor's actions. Studies on joint actions have used the "social Simon effect" to explain the concept of co-representation in humans. This effect is a variant of Simon effect, which states that for an individual subject performing bimanually, the behavioral reaction time is greater if the locations of response and stimulus are spatially incongruent. As opposed to the bimanual condition in Simon task, the Social Simon task employs two individuals, each responsible for one response. Tsai and colleagues used the social Simon task to explain the basis of how people interpret their partner's intentions. In this study, the subjects were ask to complete the task under the implemented belief that their biological partner was performing in another room, although all the partner's responses were actually generated by the computer. This study suggested that the co-representation of other's intentions and actions are by default biologically developed in the human motor system and that the joint

compatibility effect could be observed in an individual even when one of the interacting partner was not concurrently performing in the same room (Tsai et al. 2008).

Another area of interest amongst the investigators of human joint actions has been to compare the strategies used by agents in intra- and inter-personal coordination in a movement context. Braun and colleagues used a continuous motor version of classical prisoner's dilemma and found Nash solution for the dyadic configuration, as compared to the cooperative solution for the bimanual configuration. The Nash equilibrium solution, a concept derived from the classical game theory, suggests that in a two-player game, each player chooses a strategy such that either player gains nothing by modifying only their own strategy (Braun et al. 2009). The results of this study were in contrast to those found in the cognitive discrete games such as the classical prisoner's dilemma in which the solutions were mainly cooperative in a dyadic scenario. In summary, the study suggested that the game theory can be used as a tool to study a variety of other sequential joint action games in which the players interact over a sequence of time steps.

Progress in understanding the neural and cognitive processes underlying joint actions has been slow as cognitive neuroscientists have for the most part, studied individual brains (Sebanz et al. 2006). Based on the initial belief amongst cognitive neuroscientists that the processes that facilitate joint actions in humans can be understood on an individual level, many studies have tried to study these social processes by presenting social pictures or videos to the subjects (Lieberman 2007). Although these studies have found some markers of social interaction in individual brains, how these brain regions behave during dynamic interaction situations is not well

known (Liu and Pelowski 2014). As the need to develop social robots that could interact with humans in real time is being increasingly felt, the number of studies on human joint actions that are focusing on simultaneous acquisition of data from multiple brains are increasing. Studies focusing on issues such as "two- person neuroscience" (Hari and Kujala 2009) and difference between online and offline social cognition (Schilbach et al. 2014) have addressed the importance of social interaction between multiple individuals. This is necessary to understand the variability of human behavior under different contexts.

A major challenge in the field of joint actions is to be able to define a common basis on which the coordination between individuals can be grounded. A study by Kupferberg and colleagues, suggested that the phenomenon called "action-perception coupling" (Kupferberg et al. 2012), automatically serves our ability to infer and simulate the intentions of the co-actor's movements. Principles of motor resonance, motor stimulation and mirroring have explained the close links between action and perception (Obhi and Sebanz 2011). The action perception coupling has a direct effect on the movement trajectory of the observer when observing the movements of the actor. The concept of this theory developed from the discovery of the so called "mirror neurons" in the premotor cortex of macaque monkeys, which fired both with monkey's actions and passive observation of the experimenter performing the same actions (Brass et al. 2001; Jeannerod 1994). However, the lower level mechanisms such as the action-perception are not enough to develop a concrete basis for joint actions. The large number of possible combinations of feedbacks, contexts and agencies in studying joint actions makes it a field that is quite challenging.

Interaction between individuals can be categorized as 1) spontaneous, incidental interpersonal interaction or 2) instructed, intentional interaction (Jung et al., 2011). The former has been employed mostly in behavioral studies in which coordination between the two individuals is usually compared to their own individual performance. The latter has been studied in terms of goal directed joint actions in which the subjects either compete or cooperate to complete the joint action task. The instructed interpersonal coordination can be further divided into turn-based and concurrent interactions in which the subjects involve either independently or interdependently (Liu and Pelowski 2014). For the purpose of this thesis, we designed a paradigm in which the subjects were involved in an instructed interpersonal coordination. Following the instruction to the dyads about the necessity of collaboration in order to complete the task, we were interested to see the learning that took place and the strategies that the different dyads used to collaborate in a joint action.

## 1.2 FACTORS AFFECTING THE PERFORMANCE IN JOINT ACTIONS

Joint actions in humans have been studied under various contexts such as the ones requiring short term predictions through action-perception links (Marsh et al. 2009; Schmidt and Richardson 2008), to those requiring long-term planning, to those that may only require the partners to develop mental representations of each other. Although the neural and cognitive processes involved in these different contexts might vary, there is a need to identify and work on the common links between them to ensure proper execution of joint actions. Below are some of the most common factors that have been found to affect the performance in joint actions studies to date.

## 1.2.1 FORMING REPRESENTATIONS

Various studies on human interactions have identified that coordination is possible through action observation and simulation and that forming representations is unnecessary (Marsh et al. 2009; Schmidt and Richardson 2008). However, there are situations where the partners in a joint action are not provided with visual feedback regarding their partner's actions or part of the task. In such cases, forming representations, in which a person understands and shares the partner's part of the joint task, is of great importance for a successful collaboration. This concept called co-representation, has been studied in conditions of limited feedback regarding the partner. In an EEG study by Tsai and colleagues, subjects were asked to participate in a social Simon task under an implemented belief of interacting with an unseen biological partner. Even though the responses from the so-called partner were actually coming through a computer, the subjects showed a similar activation pattern as in a condition when two subjects concurrently perform a task. The study suggested that the process of co-representation is a phenomenon that is evolved biologically by default in humans (Tsai et al. 2008). In another EEG study by Hollander and colleagues, activation of motor areas in the brain of the non-acting person were shown when the actor performed (Hollander et al. 2011). Another study suggested that the co-actors could predict each other's actions using certain events in the environment, if the representations of each other's part in the task are formed (Sebanz et al. 2006). This also leads to the ability to incorporate the 'what' and 'when' of other's actions in one's own actions (Sebanz et al. 2006).

**1.2.2 JOINT ATTENTION**

For a joint action to be successful, the participating individuals should be able to direct and link their attention to the common object of interest. Joint attention is made possible through a communication channel such as pointing gestures, head tilts, eye gaze, etc., between the subjects. For example, therapists manipulate joint attention to help patients with autism, who have difficulty attending to a particular object. This deficit reduces an autistic person's ability to interact as they cannot maintain their gaze with others. Joint attention has been found to be a very crucial component in social interactions as the knowledge of what the partner is attending to can help one to generate actions complementary to the partner (Bayliss and Tipper 2005). Studies on human robot interactions are particularly focusing on the importance of joint attention. A study by Huang and Thomaz proposed a computational model of joint attention to study human-robot joint actions. They divided the joint attention skill into three components 1) responding to joint actions, 2) initiating joint actions and 3) ensuring joint actions. The study suggested that humans have a better sense of robot's part of the task when the robots respond to joint attention. Joint attention ensures better task performance and thus is realized as a natural behavior in joint actions (Huang and Thomaz 2010).

**1.2.3 PREDICTING INTENTIONS**

The most crucial difference between the cognitive capabilities of humans and other species is the ability to predict and share intentions with others. Understanding intentions is inevitable in human joint actions as it provides the "interpretive matrix" (Tomasello et al. 2005), which gives the individuals a sense of what their partners are

planning to do. A study by Becchio and colleagues suggested the role of social intentions on action in which the subjects either passed the object to the partner or kept it at a location without passing (Becchio et al. 2007). The study showed that the kinematic patterns in the subjects' movements with an intention of passing were different from those in the non-passing situation. Another study by Becchio and colleagues further emphasized the importance of observed kinematic patterns in understanding and discriminating the intentions of the partner (Becchio et al. 2012). This fact could be used for the classification of strategies used by individuals involved in a joint action. However, the matter of whether the motor simulation, i.e. the understanding of actions (through mirror neurons) is sufficient to predict the intentions of the partner is a controversial matter. In a study by Jacob and Jeannerod, they showed that through action observation, the observer can predict the motor intentions (Jacob and Jeannerod 2005), (i.e. what) but not the social intentions (why) of the partner's actions (Obhi 2012).

### 1.2.4 MONITORING

This process helps the co-actors determine to what extent the goal has been achieved (Botvinick et al. 2001). Monitoring each other's actions in joint actions is important if the task is to be completed by the parallel combined efforts of the participating agents. Vesper suggested that monitoring is often understood as error detection, i.e. the partners in a joint action detect errors in each other's part of the task (Vesper 2010). Studies on effects of action observation have identified slowing down after making an error as the behavioral marker of monitoring. Monitoring the partner's part of task has found to be effective in improving the performance of joint actions.

Another study showed that if two pianists played a piano duet together, synchrony between their tones was most when they could monitor or hear other's and own performance as opposed to when they could hear only their own performance (Goebl and Palmer 2009). In the case of joint actions, effective monitoring implies that the individuals are aware of their partner's error and they take corrective actions to make the joint action successful. Continuous monitoring is also important in situations where one partner is trying to be as predictable as possible, i.e. providing indirect cues about his actions, such as increasing the speed abruptly or moving in different direction. In the absence of total feedback where continuous monitoring of each other's actions is not possible, performance of the joint action could be improved by monitoring the common goal or individual goal, depending on the task requirements.

### 1.2.5 SENSE OF AGENCY

In a situation where multiple agents are performing in parallel, the sense of agency of an individual in a collaborative effort is the awareness about which ones out of the multiple actions being performed were executed by him or her. In case of a single individual performing an action, the sensory effects of his or her actions helps to experience the agency (Frith 2000). Humans have the ability to better discriminate the after effects of self-generated motor commands than the ones generated by others. The behavior and the effects of our motor commands are predicted by the internal forward model of the Central Nervous System (Wolpert et al. 1995), by comparing the actual and the desired outcome. When we perform in collaboration with a partner, the forward model predicts a discrepancy between the desired and the actual outcome and helps us discriminate between the actions performed by the partner and ourselves (Sato and

Yasuda 2005). In ambiguous situations where the joint action task can only be completed by the shared efforts of two or more individuals, having a sense of agency is the first step towards making corrective movements to ensure accuracy. Specifically, it is almost inevitable to have a sense of agency in the situations of limited feedback where direct observation of partner's actions is not possible. Overall, having an accurate sense of agency could be very challenging for the partners in concurrent joint actions as the actions are being carried out at the same time and results in similar effects (Farrer and Frith 2002).

## 1.3 NEURAL CORRELATES OF JOINT ACTIONS

The need to investigate the neural basis of joint actions was felt amongst the neuroscientists as a person's reaction to the behavior of his or her interacting partner is linked to the relation arising between that person and the partner, which in turn can be understood by studying the brain activity of the interacting individuals (Astolfi et al. 2014). The majority of the neurophysiological studies on the neural correlates of social behavior have studied individual brains by presenting social cues to the subjects and simulating conditions of joint actions. These studies have identified a few regions comprising our "social brain" (Frith 2007) such as amygdala, orbital frontal cortex and prefrontal cortex. However, how these brain regions behave in the real mutual interaction situations is not well understood (Liu and Pelowski 2014).To better understand these situations, researchers are increasingly using a technique called "Hyperscanning" which could be performed both with fMRI and EEG devices. This technique involves the simultaneous acquisition of cerebral data from all the subjects participating in a joint action (Montague et al. 2013).

With the advancement of the Hyperscanning techniques, more and more areas of human brain are being identified that are activated during such inter brain synchronization. In an opinion article by Liu and Pelowski for the Frontiers in Human Neuroscience, based on the neuroimaging studies on joint actions so far, different brain regions have been identified as being activated based on the type of interaction between individuals (Liu and Pelowski 2014). According to this issue, these studies have identified separate areas in the brain for joint actions involving turn-based interactions or concurrent interactions. Jiang and colleagues studied the brains of individuals involved in a turn-based task and found the majority of activation in the left inferior frontal gyrus (IFG) (Jiang et al. 2012). On the other hand, a study by Yun and colleagues, identified activation in frontoparietal network when participants were involved in a parallel coordination task (Yun et al. 2012). These studies suggest that different brain regions are recruited depending on the type of interaction and the representation that individuals form about their interacting partner and their part of the task.

The initial evidence regarding the neural basis of joint actions was found in the mirror neurons in the macaque's brain. However, there has been a debate about whether the mirror neurons form the locus of the coordination mechanisms in human brain. In another study the researchers shed light on the importance of the mirror network in the understanding of each other's motor goals and intentions in a joint action (Rizzolatti and Sinigiglia 2010). They studied the so called "mirror mechanism" in the parieto-frontal cortical circuit in the monkey brains, which is said to have mirroring properties (Rizzolatti and Sinigiglia 2010). This study suggested that this mirror network gives

the individuals an understanding of the actions of their interacting partner(s) 'from the inside', which ultimately helps them to develop an understanding of their partner's goals and intentions. There have been other studies that do not support the central role of mirror neurons in executing joint actions, as discussed below.

In a recent fMRI study by Kokal and colleagues, they argued that the tasks of translating and integrating information are done by separate areas in the brain (Kokal et al. 2009). This study suggested that the putative mirror neuron system (pMNS; Gazzola et al. 2006), controls the task of translating between motor and visual codes whereas areas such as prefrontal, posterior parietal and temporal lobe adjacent to the putative mirror neuron system integrates this information to help the individuals to achieve common goals (Kokal et al. 2009). This study was followed by another study in which the researchers showed that the pMNS is indirectly involved in the information integration process by sending information to the areas that actually integrate the information. They concluded that the flow of information during joint actions is from the inferior part of the brain (where the pMNS is located) to the posterior part of the brain.

## 1.4 ROLE OF FEEDBACK IN HUMAN JOINT ACTIONS

Humans rely on the information provided by their partner to learn new skills during inter-human interactions. Visual, auditory and haptic feedback are the most common sources of information provided to the agents when studying joint actions. Here we discuss several studies that have demonstrated the role of feedback in human joint actions.

## 1.4.1 VISUAL FEEDBACK

Unintentional movement synchronization occurs between individuals as soon as the sensory information is exchanged between them. Schmidt and O'Brien showed that out of all types of sensory information that could be exchanged between individuals, synchronization is inevitable if the visual information about the co-actor is available to the observer (Schmidt and O'Brien 1997). Richardson studied the synchronization taking place between two participants rocking in chairs next to each other (Richardson et al. 2007). When the frequencies of the chairs were manipulated, one or both the participants adjusted their movement trajectories to maintain the level of coherence. The results of this study demonstrated the so called 'Interference Effect' (Brass et al. 2001; Kilner et al. 2007; Sebanz et al. 2003; Stanley et al. 2007), according to which, when people watch movements different to those performed by themselves, an increase or a decrease in the reaction times take place due to spatial incompatibility (Brass et al. 2001; Sebanz et al. 2003). The neural basis for this unintentional synchronization is believed to be the Mirror Neuron System which activates when the observer observes the co-actors' actions and develops a representation of it.

However, the aforementioned 'Interference Effect' leads to an argument that arises from the motor contagion theory. According to this theory, when an observer observes an action that is incongruent to his or her own action, bias and variability is introduced into his or her own action. This suggests that the adjustments that the observer makes to his own movements when watching the actor's actions has nothing to do with movement synchronization.

Lorenz and colleagues studied the role of visual information exchange in unintentional synchronization through a repetitive target-directed arm movement task (Lorenz et al. 2014), in which one of the subject's movement path had an obstacle. They observed that in order to maintain the level of synchronization, the actor without an obstacle increased the dwell times in order to allow the actor with an obstacle to maintain the level of synchrony by increasing the movement velocity. This means that one actor acts as the compensator and the other actor tries to be as predictable as possible in order to assist the compensator (Lorenz et al. 2014).

## 1.4.2 HAPTIC FEEDBACK

The continuous exchange of haptic information between the co-actors in a joint motor task leads to joint motor interactions. An example of haptic interaction is that between the physiotherapists and their patients. In order to develop efficient social robots, such as the ones used in robot assisted therapy, we need to find out the strategies that mechanically coupled humans use to counteract perturbations. Melendez and colleagues investigated how two individuals when mechanically coupled, behave when either one or both the subjects are exposed to mechanical perturbations during a joint motor task (Melendez et al. 2015). They highlighted the role of haptic feedback during joint motor interactions and found that the different dyads followed a common trend of strategies used to counteract the perturbations.

Another study with a focus on human-robot interactions suggested the importance of physical coupling in improving the performance of individuals in sensorimotor collaborations as compared to only virtual coupling. Various shortcomings related to the use of visuomotor tasks in order to study sensorimotor

collaborations were mentioned in this study, in terms of the limited degree of freedoms used in such non-physical collaborations. Although, haptic feedback has been studied in combination with visual and other sensory feedback for improving the performance of joint actions, the role it plays alone has not yet been studied (Sawers and Ting 2014). Such studies are important considering the delays in processing sensory information that might occur in some cases as compared to the somatosensory information that might be processed faster and lead to better interactions.

## 1.5 OBJECTIVE OF THE THESIS

Research in the field of joint actions to date has mainly addressed how the interaction between agents takes place in the presence of feedback (visual, auditory or haptic) about the other agent. Majority of the research has focused on how the interaction between individuals take place when the subjects are physically coupled. A study by Sawers and Ting emphasized the importance of haptic interactions to develop rehabilitation robots that could physically interact with humans using the principles of cooperative sensorimotor collaboration derived from human-human physical interactions (Sawers and Ting 2014). Similarly, there have been other studies that have highlighted the importance of feedback in improving performance and in enabling the individuals to better interpret each other's intentions. A series of studies by Becchio and colleagues demonstrated how the two subjects in a joint action can predict each other's intentions by observing the kinematic patterns (Becchio et al. 2008; Becchio et al. 2010; Becchio et al. 2012).

However, limiting our understanding of human joint actions to situations in which the feedback is available to the agents may obscure us from understanding the

situations devoid of feedback. A study by Penders and Ghosh focused on human robot interactions in the absence of visual and aural feedback. In order to develop robots that could interact with humans in real world environment, it is necessary that to explore the situation when there is little source of information about the interacting partner (Penders and Ghosh 2015). To achieve this feat, we need to explore strategies that two humans would use to interact in situations when forming mental representation of each other's actions is necessary in order to collaborate. Studying this situation is imperative to account for the variability of human behavior that would be introduced in the absence of feedback as opposed to when the feedback is present.

The objective of this thesis was to develop better and a complete understanding of joint actions in humans in situations when they consciously try to collaborate without much information about the partner. The very first question that came to our mind when designing such a setting was whether the subjects would be able to attend to a common object of interest without any explicit knowledge about the partner's intentions and behavior towards the task. The co-actors often coordinate by forming a "perceptual common ground" (Clark 1996), that enables a performing agent to allocate his or her attention towards a location where the co-actor would perform his or her actions (Tipper 2010; Brennan et al. 2008; Tomasello and Carpenter 2007). We hypothesized that this common ground would also allow the agents to perform in the situation that we re-created in the laboratory.

To simulate this common ground, we designed a virtual reality game which gets completed by the shared efforts of both subjects in a dyad. The game included a cursor, a starting position and four target positions. Subjects were instructed to move the cursor

from the starting position to one the four target positions and then back to the starting position. Motion of the cursor depended on the arm movements of both subjects, i.e. the mean of their simultaneous (but not necessarily synchronous) individual actions. We provided the subjects with cursor feedback and any other information about the other subject was withheld. To further test the learning that would take place, we introduced a visuo motor rotation of 30° to either one or both the subjects' movements in separate blocks.

Our first aim was to see how much of learning took place in the absence of feedback, i.e. how well the subjects were able to predict each other's intentions over the blocks. Most importantly, we wanted to test whether the subjects were able to infer their partner's movement characteristics, (i.e. the direction, amplitude and time, in the absence of a separate kinematic feedback about the partner's motion) and incorporate them in their own action plan to make the cursor movement accurate. To give the subjects an indication of their progress in collaborative learning, we provided them with an audio feedback regarding the successful trials. We supposed that this might give the dyads a chance to improve their performance as they were required to complete 60 successful trials in each block. A better interpretation sense between the partners would result in a greater accuracy. To achieve high accuracy, subjects must be coordinated in both space and time.

Moreover, we introduced a visuomotor rotation of 30° to either one or both the subjects' movements without any prior instruction to the subjects. Learning to adapt to the visuomotor transformations takes place through the strategies developed by CNS which updates the feedforward and/or feedback motor commands (Saijo and Gomi

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2010). We wanted to see whether there is a difference in the way the motor commands were for the dyads, in terms of changes in the reaction time or the movement errors. Since the visual feedback of the cursor was available to the subjects, we were interested in seeing whether the subjects were making corrective movements to nullify the rotation effects and maintain the accuracy.

Our second aim was to see whether the subjects develop any collaboration over the blocks. Since the only visual feedback that the subjects received was that of the common cursor, the subjects were expected to either predict the partner's errors and make corrective movements or be as predictable as possible to the partner. However, we also realized the possibility of an individualistic approach, i.e. a condition in which no collaboration is offered from either one or both the subjects in a dyad. This was quite possible as the two subjects in every dyad of our study were socially unacquainted. Previous studies on joint actions have identified both cooperative and competitive strategies based on the context in which the task was performed. Specifically, the second aim of our study was to categorize these strategies based on various kinematic metrics to compare the contribution of each subject in the sensorimotor collaboration.

CHAPTER 2

MATERIALS AND METHODS

## 2.1 SUBJECTS

Twelve right handed (aged 18-65) subjects participated in this study. All subjects were naïve to the experimental conditions and had no history of neurological disorders. Experiments were performed at the Department of Biomedical Engineering at Arizona State University. Subjects participated in pairs of two (dyads) and were socially unknown to each other. The study was approved by the Institutional Review Board.

## 2.2 SYSTEM DESIGN: A VIRTUAL REALITY BASED ENVIRONMENT TO CAPTURE THE JOINT ACTIONS OF A PAIR OF SUBJECTS (DYADS)

We used the OptoTrak 3020 motion tracking device, Northern Digital Inc., Waterloo, Ontario, to develop a virtual reality environment which captures the finger-tip movement data of the two subjects. The virtual reality system is comprised of five components:

1. Optotrak Motion Capture System

2. OptoTrak System Computer

3. Control System Computer

4. Data Visualization Computer

5. Projector System

The Optotrak System captures the motion of the subjects. The OptoTrak Computer sends the motion capture data over the network to the Control System Computer. The Control System Computer processes the motion capture data into game

coordinates, chooses game target object positions based off of settings chosen by the experimenter, and logs the data. The Control System Computer then sends the positions of the cursor, target, and other game parameters over the network to the Data Visualization Computer. The Data Visualization Computer then displays the video game using the Projector System. Python and C were the programming languages used to build the entire program.

**2.2.1 MODES OF OPERATION**

The virtual reality system has three primary modes of operation:

1. <u>Calibration</u> - This was done to define the origin of the subjects' markers. Here, the individual coordinates of each subject were mapped on to the game coordinates.

2. <u>Independent Control Mode (each subject controls their own cursor)</u> - This mode was designed to make the subjects accustomed to the virtual reality game one at a time and to give them a chance to choose their comfortable workspace. Each subject had one marker on the fingertip and they controlled a cursor displaying their hand position independent of the other subject.

3. <u>Cooperative Control Mode (subject movements are combined together and then mapped to cursor movement)</u> - This is the mode in which the actual game was played collectively by both the subjects. The game was designed such that cursor movement was the mean of the simultaneous movements of both the subjects in a dyad.

### 2.2.2 DESIGN CONSIDERATIONS

1. <u>Interface to control the virtual reality system</u> - The system is controlled through a graphical user interface. This was done to facilitate altering the game settings, for e.g. changing the mode of operation.

2. <u>Data collection</u> - The data was collected at a sampling frequency of 100 Hz. To maintain the proper organization of data files, a database format called HDF5 (Hierarchical Data Format 5) was used which also reduced the memory required to store the data files.

3. <u>Performance requirements</u> - To make the player experience appear to be real-time (i.e. run at 30+ Hz), the data logging ran at an uninterrupted 100 Hz. These real-time requirements led to decision to separate the computers into roles (i.e. data collection, data conversion and logging, data visualization), and separate programs into multiple processes. Usage of Cython to speed up code, and TCP protocols to communicate across computers was necessitated as a result.

### 2.3 EXPERIMENT DESIGN

Subjects were seated in chairs adjacent to each other and had an opaque shield in between them so as to block the view of each other's arm. Subjects were instructed to not provide each other with verbal cues. A projector screen was placed in front of the subjects on which the virtual reality game was projected. The lights were turned off to minimize the vision of one's own arm. Subjects were however provided with cursor feedback and auditory feedback related to the successful trials. The game was designed to be a 'ball in a hole' game which had 4 peripheral targets and one center starting position (see below).
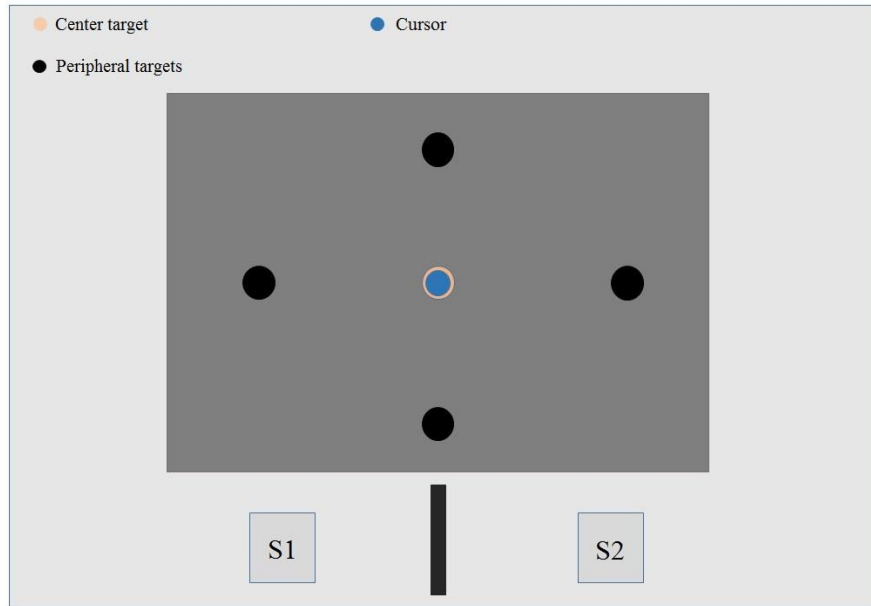
**Figure 2** Virtual reality setup used in the experimental trials; 4 peripheral targets; 1 center target; 1 cursor; 2 subjects performing with no visual feedback

## 2.3.1 CALIBRATION PROCEDURE

Each subject had an IR marker fixed to the index finger tip of the right hand and one reference marker in front of each of them. In order to find the origin of the subject's markers, a calibration procedure was done which took approximately 5 seconds. This ensured that each subject's coordinates were mapped to the common game coordinates.

## 2.3.2 GAME PROTOCOL AND INSTRUCTIONS

The game was displayed on a projector screen placed in front of subjects. The game consisted of 4 peripheral targets and one center target. Subjects were required to move the comet, i.e. the cursor (ball) from the center starting position to one of the 4 peripheral targets wherever the earth (hole) appeared and return back to the starting position. A successful trial consisted of-

1. Moving the cursor from center to the peripheral target

2. Fitting cursor within the peripheral target borders

3. Fitting cursor back within the center target borders, within a time constraint of 2 seconds

In order to familiarize subjects with the cursor movement in relation to their movement, each subject in a dyad was exposed to independent control mode before beginning the actual trials. In this mode the subjects independently controlled the cursor. The actual mode in which the game was played was cooperative control mode for which 4 peripheral targets were chosen.

The experimental session consisted of 7 blocks. Subjects were required to complete 15 successful trials per target in each block, i.e. each one block consisted of 60 successful trials. A 20s break was given every 10 trials to the subjects. After each block, the subjects were allowed to rest as much as they needed to.

### 2.3.3  EXPERIMENTAL CONDITIONS

In order to test the interaction between subjects, we introduced a visuomotor rotation of 30° to either one or both the subjects' motion to ensure that mapping between the subjects' motion and the cursor's motion was not always veridical. Each subject received a rotation of 15° in case of both subjects' being provided subjected to the rotation. The visuomotor rotation was provided in the clockwise direction in 7 out of the 3 blocks and the remaining 4 blocks were the control blocks. The order of the rotation was randomized for each dyad and the subjects were not informed about the rotation.

## 2.4 DATA ACQUISITION

The finger movements were recorded using OptoTrak 3020 (Northern Digital Inc., Waterloo, Ontario) 3D acquisition system. One infrared marker was fixed to the tip of the index finger of right hand of each subject and one marker was fixed in front of each subject on the fixed table. The data was sampled at 100 Hz. Before the actual experiment, subjects were asked to move their finger in the space to make sure the marker was detected by the OptoTrak system. Subjects were provided with the cursor feedback and the audio feedback regarding the successful trials. All the collected data was organized in HDF5 files to reduce the memory requirements and to enable the analysis using both Python and MATLAB (The Mathworks Inc.).

## 2.5 DATA ANALYSIS

For data analysis, we did not discriminate between the spatial locations of the four peripheral targets. The reason for providing the subjects with multiple targets in different directions was to prevent the learning of a single trajectory pattern, and thus testing the collaborative effort through a more challenging task.

The data analysis was performed using various measures of spatial and temporal coordination. All the data analysis was done using MATLAB (The Mathworks Inc.). Although we used the data from unsuccessful trials to calculate the accuracy of dyads over the blocks, only the data from the successful trials was analyzed and plotted, for the purpose of this thesis.

## 2.5.1 SUCCESS RATE ANALYSIS

The analysis of success rates of the joint action task was done to test the level of learning in the dyads with blocks, i.e. did the success rates and minimum number of

unsuccessful trials vary with the blocks. Because we considered all the targets alike, the success rate analysis did not account for the success rates for a particular target. However, the subjects were instructed to complete 15 successful trials per target in each block in order to move to the next block. Through this analysis, we were also interested to see the differences in performance of the dyads for the blocks with no rotation (control blocks) and the blocks with visuomotor rotation (test blocks). The accuracy was calculated as-

$$\% \, Success \, Rate = \frac{Number \, of \, successful \, trials}{Total \, numer \, of \, trials}$$

## 2.5.2 SPATIAL MEASURES OF COORDINATION

## 2.5.2.1 COMPARING THE WORKSPACE OF SUBJECTS IN A DYAD

As a first spatial measure, we analyzed and compared the amplitude of movement trajectories of the two subjects in each dyad. We considered a possibility of the differences in the movement amplitude for the subjects as they were asked to determine their own comfortable movement region in space during calibration. As the subjects were unable to see each other both during calibration and the task, the probability of both unequal and similar movement amplitudes during the joint action task was equally considered prior to this analysis.

The data was captured continuously at a sampling rate of 100 Hz until the completion of 60 successful trials in each block and the actual starting position for a subject making an outward reach to a peripheral target was not necessarily the same as the center target position, as it ideally should be. Moreover, this starting position was

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different for the two subjects in each dyad. Therefore, we used a common reference

(b), explained below, for comparing the reaching workspace of the two subjects.

To conduct this analysis, we calculated the ratio (r), calculated as-

$$r = a/b$$

*a = length of a linear path connecting the actual starting position and the endpoint during a single outward reaching movement*
*b = length of a linear path connecting the center and peripheral target, a constant, as all the targets were equidistant from the center target*

This ratio was calculated for every successful trial and thus we had 420 ratios

corresponding to the 60 successful trials for each of the seven blocks. The ratios were

then averaged over the blocks and were plotted against the respective block numbers.

For any trial, a value of this ratio close to 1 indicated that the endpoint for that trial was

closer to the corresponding target position. Therefore, the mean value of this ratio over

a block gave us an approximate estimate of the endpoint distributions around the four

targets for that block.

**2.5.2.2 DIRECTION ERROR AT PEAK VELOCITY**

In reaching movements made to visual targets, the point of peak velocity is a

strong predictor of a subject's execution error as majority of the compensatory

adjustments to the movement to ensure reach accuracy, are made after the point of peak

velocity. Stewart and colleagues, studied the factors influencing the planning and

adjustments in reaching movements made to 3D targets and found that peak velocity

and target distance accounted for the maximum amount of variance in movement

characteristics (Stewart et al. 2013). Although the above study was done with

individual subjects, we were interested in studying similar mechanisms in case of joint actions between two individuals. In our paradigm, we kept the peripheral targets at equal distances from the center target to eliminate any effects that target distance could have in movement planning. Our main focus was to test how the subjects in a dyad simultaneously adapts to the visuomotor rotation by accommodating the action plan of their partner into their own in addition to making adjustments to their own movements.

Direction error at peak velocity ($\boldsymbol{\theta}_V$) was calculated as the angular difference between the ideal trajectory (linear path connecting the starting position to the peripheral target) and the vector connecting the starting position with the point of peak velocity. Although the starting position for outward reach to a peripheral target was different for the two subjects in a dyad in every trial, we were able to compare the angular deviations for both the subjects at points of their respective peak velocities since the 3D position coordinates for both the subjects were mapped to the common 2D game coordinates. The counterclockwise deviation was considered to be negative as opposed to the positive clockwise deviation which was provided during visuomotor rotation in test blocks.

Apart from calculating the direction errors at the peak velocity for the subjects, we also analyzed the direction errors for the cursor to make a collective analysis of how exactly the subjects adapted and de-adapted to the visuomotor rotations to maintain the accuracy of the cursor position. At any point the cursor's angular deviation from the ideal trajectory was calculated as the average of the angular deviations for both the subjects. Also, the main reason behind providing the subjects with online cursor feedback was to facilitate the online error corrections during the course of movement.

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The direction errors at $V_{peak}$ so obtained for the subjects and the cursor were averaged across all the blocks and were plotted along with the error bars depicting one standard deviation, against the block numbers. The values of $\boldsymbol{\theta}_V$ were initially obtained in radians and then converted to degrees through multiplication with $(180/\pi)$. Since, all the four targets were alike in terms of distance from the starting position, we did not conduct any direction error analysis based on target location, although the dyads might have had differences in the compatibility towards reaching to the targets in four different directions.

## 2.5.2.3 DIRECTION ERROR AT ENDPOINT

Direction error at endpoint ($\boldsymbol{\theta}_E$) was calculated as the angular difference between the ideal trajectory and the linear path connecting the starting position with the point of movement offset, when reaching to a peripheral target. Endpoint or point of movement offset was defined as the first point where the direction of the trajectory was reversed in order to make a reach 'back' to the center target. The endpoint direction error for the cursor was calculated as the average of the endpoint direction errors for the subjects in their respective workspaces. Since we included only successful trials in our analyses, we expected that the mean endpoint direction error for the cursor over the blocks would be closer to zero depicting accurate reaches to the peripheral targets in terms of direction.

The direction error analyses at endpoints was done in succession to the previous analyses at points of peak velocities in order to derive a better sense of the roles that subjects in each dyad took to collaborate in the joint action task. In essence, by calculating $\boldsymbol{\theta}_E$ on a trial by trial basis, we wanted to see whether the subjects assigned

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specific roles to themselves or whether they switched roles in order to maintain the accuracy of the cursor. For example, one subject might entirely absorb the visuomotor rotation by moving in opposite direction to the rotation, regardless of which subject is rotated out of both the subjects. Another example would be where both subjects might adapt to rotation to varying degrees.

We obtained 60 direction errors per block, i.e. a total of 420 values of $\boldsymbol{\theta}_E$, over the course of 7 blocks for each dyad. The values of $\boldsymbol{\theta}_E$ were initially obtained in radians and then converted to degrees through multiplication with $(180/\pi)$. These values were then averaged across the blocks and plotted along with the error bars depicting one standard deviation, against the block numbers. Positive values indicated that the average deviations were clockwise and negative values indicated the average counterclockwise deviations.

## 2.5.3 TEMPORAL MEASURES OF COORDINATION

Along with analyzing how the subjects coordinated with each other in terms of direction and distance, we also analyzed the coordination in terms of mean movement time during the outward reaching movements made to the peripheral targets in all the seven blocks. Following the time constraint of 2 seconds given to the subjects for making an outward reach to the peripheral target and returning to the center target, we expected the movement time to be closer to 1 second for an outward reaching movement. For the purpose of plotting the results, we averaged the mean movement time found for the seven blocks for each subject and plotted them against the dyad number along with the error bars each representing one standard deviation.

CHAPTER 3

RESULTS

Since in our analyses, we did not include the analyses of unsuccessful trial data, the focus of our analyses was the strategies that the subjects used in order to achieve a particular success rate, i.e. how the success rate was achieved.

## 3.1 SUCCESS RATE ANALYSIS

This analysis was done in order to get an idea of how well the dyads understood our joint action task in terms of having lesser number of unsuccessful trials. Two out of six dyads (dyad 2 and 4) had notably smaller success rate as compared to the other dyads. Dyad 1 had a very high success rate of 95.24%, thus being the most successful dyad in terms of least number of unsuccessful trials. Highest success rate for dyad 1 also suggests that the dyad 1 took the least amount of time to complete the experimental session.
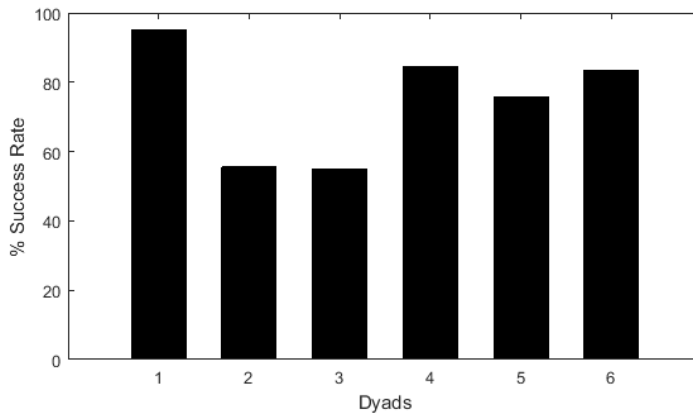


**Figure 3.1** Success rate analysis; % success rates for each of the 6 dyads are a plotted against the dyad number

## 3.2 COMPARISON OF MOVEMENT AMPLITUDES

We analyzed the ratio (r), discussed in data analysis section, to compare movement amplitudes for the subjects during reaches to peripheral targets, i.e. a larger ratio meant a

larger movement amplitude. In 4 out of 6 dyads, we observed a pattern where the changes in the values of (r) for the subjects were in near confirmation to the changes in the corresponding values for their partners, i.e. if the value increased for one subject, it decreased for the partner and vice versa.

For dyad 1 (Figure 3.2), as the values of r suggests, the path lengths were much larger for subject 1 (S1) as compared to subject 2 (S2).
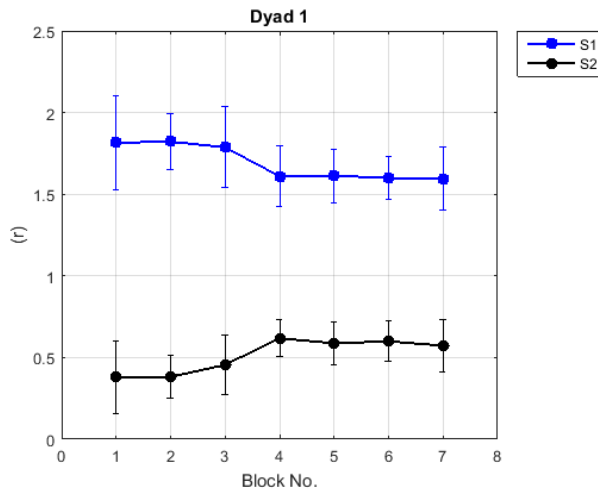


**Figure 3.2** Mean values of r for the seven blocks for dyad 1; error bars depict one standard deviation; (S1- 1.62±0.22, S2- 0.52±0.18)

Interestingly, the values of r changed simultaneously for both the subjects from block 3 to block 4, i.e. r decreased for S1 and increased for S2 by almost the same magnitude. Although the reason for this change is not entirely clear, the simultaneous adjustment suggests that either of the two subjects were able to predict and adjust to the changes made to path lengths by their partner, with the help of common cursor feedback. For other blocks, the values of r were nearly constant from one block to another, i.e. the subjects maintained a nearly constant linear path length. Also, there were no observable changes in the path lengths for dyad 1 in the test blocks as compared to the control blocks.

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In dyad 2 (Figure 3.3), S1 seemed to be contributing more to the cursor movement as S1 was making notably larger movements compared to S2, thus compensating for the 'under-reaching' movements of S2 and helped the dyad to maintain the cursor accuracy. The values of r for S1 increased over the course of first three blocks as opposed to the decrease in values for S2.
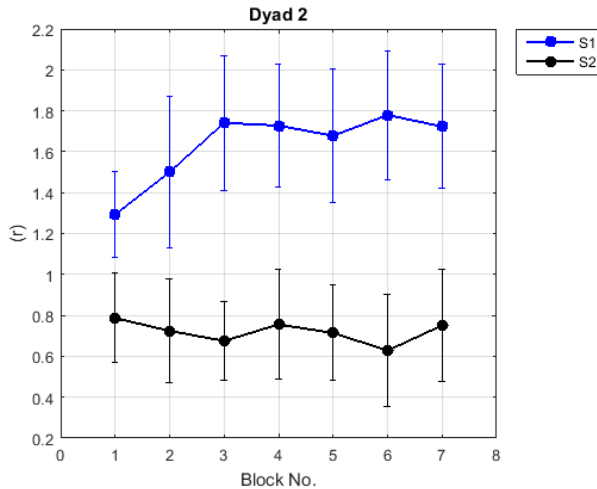


**Figure 3.3** Mean values of r for the seven blocks for dyad 2; error bars depict one standard deviation; S1- $1.63\pm0.34$, S2- $0.71\pm0.25$

This might have been a result of the initial cursor feedback- based adjustments by S1 after the introduction of unanticipated visuomotor rotations in the second block. It is possible that in an effort to counteract the visuomotor rotations, S1 moved in the direction opposite to visuomotor rotations and made larger movements and at the same time compensated for the shortening path lengths of S2. In subsequent blocks, there was no observable pattern of change in the values of r. Also, both the subjects in dyad 2 had slightly larger variability in the mean values of ratio (r) as compared to the subjects in dyad 1.

As seen in Figure 3.4, S1 in dyad 3 performed in a manner similar to S1 in dyad 2. However, S2 in dyad 3 made much smaller movements compared to S2 in dyad 2 as evident

from the low values of r. Also, the values of r for S2 in dyad 3 decreased from blocks 1 to 3 and then became nearly constant. Similar to dyads 1 and 2, S1 made much larger movements as compared to S2 in dyad 3. After block 3, there were no notable changes in the values of r for both S1 and S2, suggesting nearly constant path lengths for both the subjects.

In dyad 5, the value of r increased from blocks 1 to 3 for S1 and decreased for S2, just as in the case of dyads 2 and 3 (Figure 3.5).
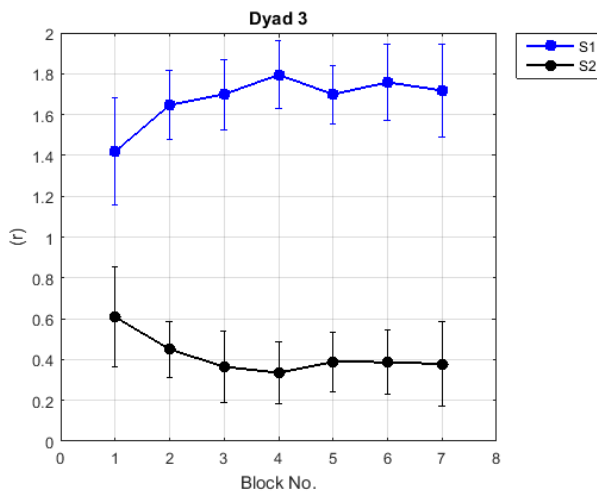


**Figure 3.4** Mean values of r for the seven blocks for dyad 3; error bars depict one standard deviation; S1- 1.67±0.22, S2- 0.41±0.19

However, in blocks 3-6, the subjects in dyad 5 maintained their respective values of r at an almost constant level, showing a better adaptation to the visuomotor rotation in the fourth and sixth test blocks as compared to dyads 2 and 3. Also, for the seventh block, the value of r decreased for S1 and increased for S2 by almost the same magnitude, thus indicating a collaborative effort. However, it is not clear why the values changed abruptly for both the subjects. Overall, S1 made much larger movements as compared to S2 in the

test blocks. This suggests a lack of cooperative effort from S2 in terms of making shorter movements as compared to S1.
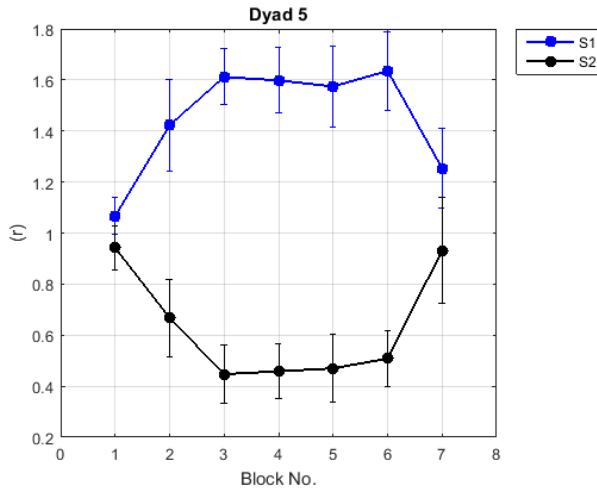


**Figure 3.5** Mean values of r for the seven blocks for dyad 5; error bars depict one standard deviation; S1- 1.45±0.24, 0.63±0.24

In dyad 4, although there were notable differences in the values of r for S1 and S2, the differences were not as significant as in dyads 1, 2, 3 and 5. As shown in Figure 3.6, S2 produced slightly larger movements during the test blocks as compared to the preceding control blocks. In other words, the values of r for S2 were significantly close to 1 during the test blocks which means a path length equal to that of an ideal trajectory, indicating an adaptation to the visuomotor rotation. There was no evident pattern in the change in values of r for S1 and the values remained nearly constant throughout the blocks, suggesting nearly constant path lengths for S1.

As compared to other dyads, subjects in dyad 6 (Figure 3.7) had the most similar path lengths in terms of the nearly similar values of ratio (r). S2 in dyad 6 made slightly larger path lengths as compared to S1 in 5 out of the 7 blocks, which were not notable eno-
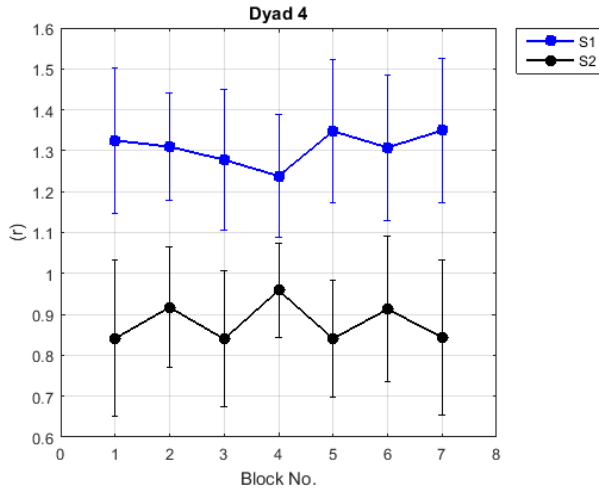
**Figure 3.6** Mean values of r for the seven blocks for dyad 4; error bars depict one standard deviation; S1- 1.31±0.18, S2- 0.88±0.16

gh as compared to the remarkable differences in path lengths for the subjects in other dyads.

In the remaining 2 blocks, S1 and S2 had nearly similar movement amplitudes in one of them whereas S1 had slightly larger amplitude than S2 in the other block. Overall, S1 was making movements nearly equal to the linear path length of the ideal trajectory whereas S2 was making slightly larger movements.
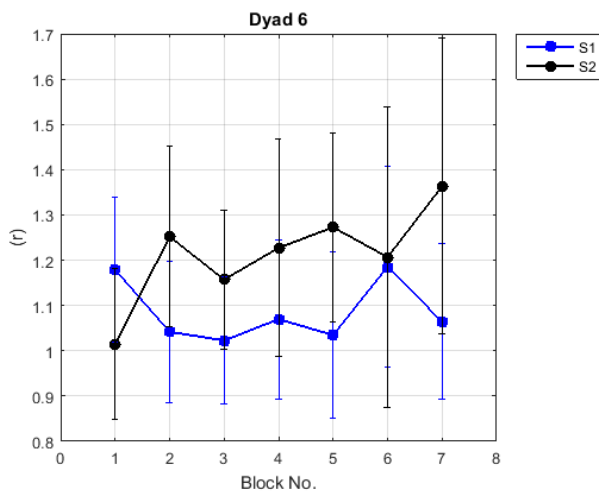


**Figure 3.7** Mean values of r for the seven blocks for dyad 6; error bars depict one standard deviation; S1- 1.09±0.18, S2- 1.21±0.26

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**3.3 DIRECTION ERROR AT PEAK VELOCITY**

**3.3.1 EXPLANATION OF THE PLOT FOR DIRECTION ERROR AT PEAK VELOCITY ($\boldsymbol{\theta}_V$)**

Direction error of the cursor at peak velocity ($\boldsymbol{\theta}_V$) during the reaching movement was calculated as the mean of $\boldsymbol{\theta}_V$ for S1 and S2. However, due to the lack of feedback regarding the partner's movements and the difference of workspaces, the points of respective peak velocities for S1's and S2's movements did not necessarily occur at the same sample point during data collection (Figure 3.8). For example, in dyad 1 for a single reach, the point of peak velocity for S1 occurred 26 samples later than for S2 in block 1. This difference had a direct effect on the calculation of $\boldsymbol{\theta}_V$, because due to the requirements of real time data collection and projection of our virtual reality task, the programming was done in such a way that $\boldsymbol{\theta}_V$ for the cursor would be calculated at the point of peak velocity for the subject for whom the magnitude for peak velocity is greater. Considering the example of dyad 1 discussed above, $\boldsymbol{\theta}_V$ was calculated at the point of peak velocity for S1 because the magnitude of peak velocity for S1 as compared to S2. The ultimate effect of the above explanation can be seen in the results for the six dyads below, where the $\boldsymbol{\theta}_V$ for cursor does not appear to be the mean of S1 and S2.

**3.3.2 RESULTS OF THE ANALYSIS**

We used two datasets to analyze the direction error at peak velocities. The first dataset consisted of the subjects' data captured directly from the OptoTrak system, without any alterations. The second set included the values that were displayed to the user, i.e. the values that were generated by passing the actual data through rotation and then using them to generate the cursor position. Therefore, the data belonging to the control blo-
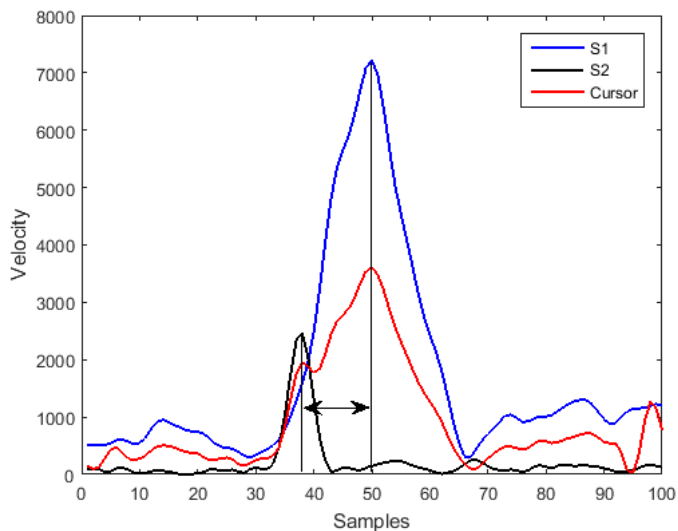
**Figure 3.8** Velocity profiles for S1 and S2 in dyad 1 for a single reach, with the double arrow depicting the time point difference in the occurrence of peaks of the respective velocities for S1 and S2

cks was same for the two datasets and different for the test blocks.

The purpose of using the first dataset in this analyses was to better analyze the process of adaptation to visuomotor rotation. In essence, we wanted to see whether the visuomotor rotation was counteracted by either one or both subjects in a dyad. Since the visuomotor rotation was provided in the clockwise direction, movements made in the anticlockwise direction were required to make the cursor position accurate, irrespective of which subject's coordinate plane was rotated.

### 3.3.2.1 POINT OF PEAK VELOCITY CAN PREDICT THE PLANNING INVOLVED IN MAKING CORRECTIVE MOVEMENTS

In all the dyads except dyad 2, direction error for the cursor in the test blocks had positive values in the range of $(0°\pm10°)$, which were low compared to the visuomotor rotation of $30°$. This suggests that subjects were performing online error corrections in order to counteract the rotation. Therefore, we wanted to analyze the initial movement plan

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of the subjects at the point of peak velocity, i.e. the direction in which the subjects were planning their movements.

In dyad 1, the subject S1 made larger corrective movements compared to S2 in order to couteract the visuomotor rotations. As shown in Figure 3.9 (b) the mean direction errors for S1 were greater compared to S2 in the negative direction (counterclockwise) direction. The subject S2 started with a large error as can be seen for the first block but in the subsequent blocks made nearly straight movements apart from some corrective movements made during the sixth block (third test block).

In terms of variability in the values of the direction errors for the two subjects, S1 had a notably larger standard deviation (S1: -8.04±67.28, S2: -2.28±31.44) as compared to S2. These standard deviations were computed across the three test blocks. The large difference in the variability of these direction errors can be attributed to the large difference in the amount of efforts that a particular subject made in order to ensure the accuracy of the cursor in terms of direction.

For S1, de-adaptation was weak in the control blocks following the fourth (second test block) and sixth blocks, but the nearly straight movement of S2 helped the dyad to maintain the cursor accuracy. Although the analysis at the point of peak velocity can not

**Table 1** Mean direction errors at peak velocities averaged across the three test blocks

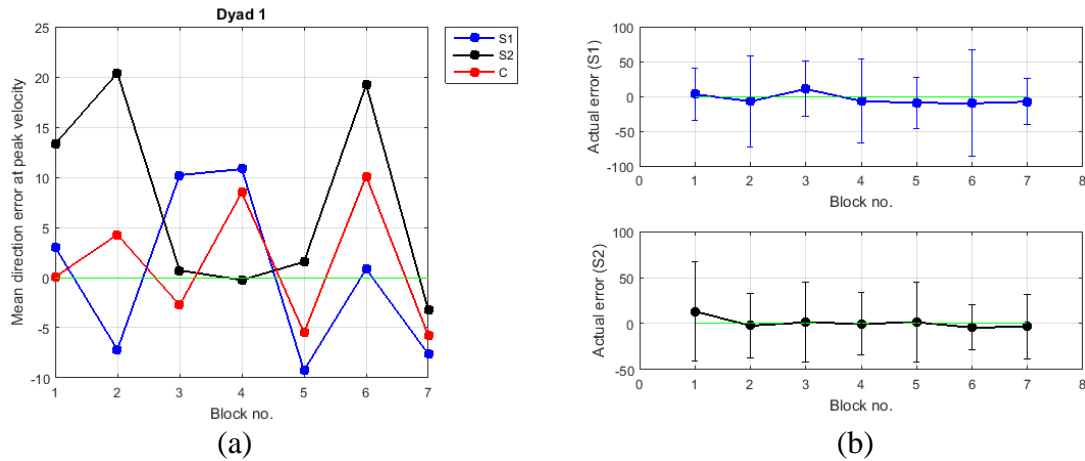|  | Dyads | | | | | |
|  | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| S1 | -8.04 | -9.79 | -10.97 | -21.28 | -11.43 | -10.09 |
| S2 | -2.28 | -2.65 | -10.42 | -17.34 | -8.02 | -6.55 |

**Figure 3.9 Dyad 1** (a) Mean direction errors at peak velocities calculated from the data being displayed to the subjects during the game post-rotation (b) Mean direction errors at peak velocities calculated from the unaltered kinematic data; error bars depict one standard deviation for each block of 60 trials; (S1: -8.04±67.28, S2: -2.28±31.44)

provide complete information about the subjects' movement plans to reach the target, this analysis gives us a preliminary information about the relative roles of the subjects in forming the action plan.

In dyad 2, S1 made most of the corrective movements in terms of mean direction error at the point of peak velocity. As shown in Figure 3.10(a), S1 made larger corrective movements in blocks 2 and 4 as compared to S2 which had very small values, i.e. S1 was making large corrective movements in the counterclockwise direction whereas S2 was making straight movements to counteract the visuomotor rotations.

Both the subjects de-adapted to the visuomotor rotations in the subsequent control blocks after the test blocks, evident from the small values of direction errors.In terms of variability in the values of direction errors over the test blocks, S1 in dyad 2 had larger a variability as compared to S2 (S1: -9.79±67.99, S2: -2.65±46.81), similar to S1 in dyad 1.

Both the subjects in dyad 3 had nearly equal values of mean direction errors at peak velocity over the three test blocks. As was required for our joint task, in the three test blocks

both the subjects made reaching movments in counterclockwise directions irrespective of

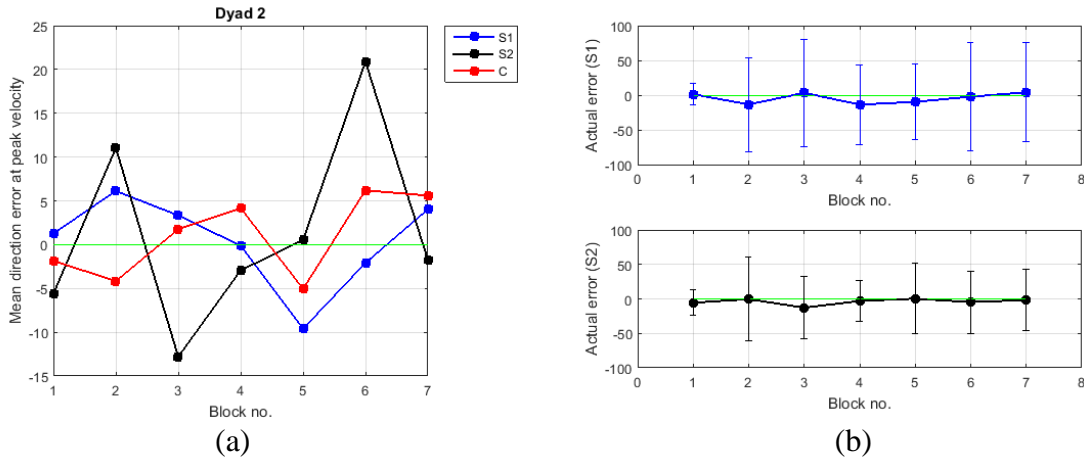which subject as rotated, thus indicating a collaborative rather than an individual approach.



(a)                                                          (b)

**Figure 3.10 Dyad 2** (a) Mean direction errors at peak velocities calculated from the data being displayed to the subjects during the game post-rotation (b) Mean direction errors at peak velocities calculated from the unaltered kinematic data; error bars depict one standard deviation for each block of 60 trials; (S1: -9.79±67.99, S2: -2.65±46.81)

The subjects in dyad 3 made sure to maintain straight movements of the cursor

during the control blocks, i.e. they were successfully de-adapting in the blocks following
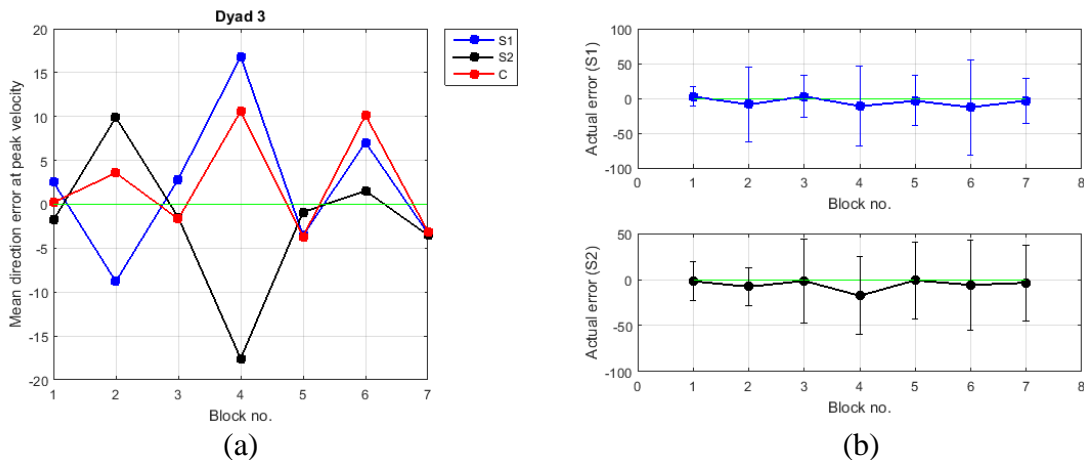
the visuomotor rotations.



(a)                                                          (b)

**Figure 3.11 Dyad 3** (a) Mean direction errors at peak velocities calculated from the data being displayed to the subjects during the game post-rotation (b) Mean direction errors at peak velocities calculated from the unaltered kinematic data; error bars depict one standard deviation for each block of 60 trials; (S1: -10.97±59.80, S2: -10.42±39.29)

Due to this collaborative effort, shown in figure 3.11 (a), the subjects unconsciously took up compensating roles alternatively, i.e. S1 maintained the accuracy of the cursor in block 2 by moving in the counterclockwise direction when S2 was undergoing visuomotor rotation and S2 maintained the accuracy in block 4 when S1 was undergoing visuomotor rotation. In terms of variability in the values of direction errors in the test blocks, S1 had higher variability as compared to S2 (S1: -10.97±59.80, S2: -10.42±39.29).

In dyad 4, the subjects had remarkably similar mean direction errors from one block to another as shown in figure 3.12 (b). As in the case of dyad 3, both subjects made efforts to adapt to the visuomotor rotation and reduce the direction error. Although, the subjects were unaware as to which one of them was undergoing visuomotor rotation, the subjects benefited from this strategy in maintaining the cursor accuracy. It is quite possible that these subjects were able to infer their partner's movement plan and thus were able to collaborate efficiently. In other words, for dyads 3 and 4, the strategy seemed to be more cooperative and less individualistic.
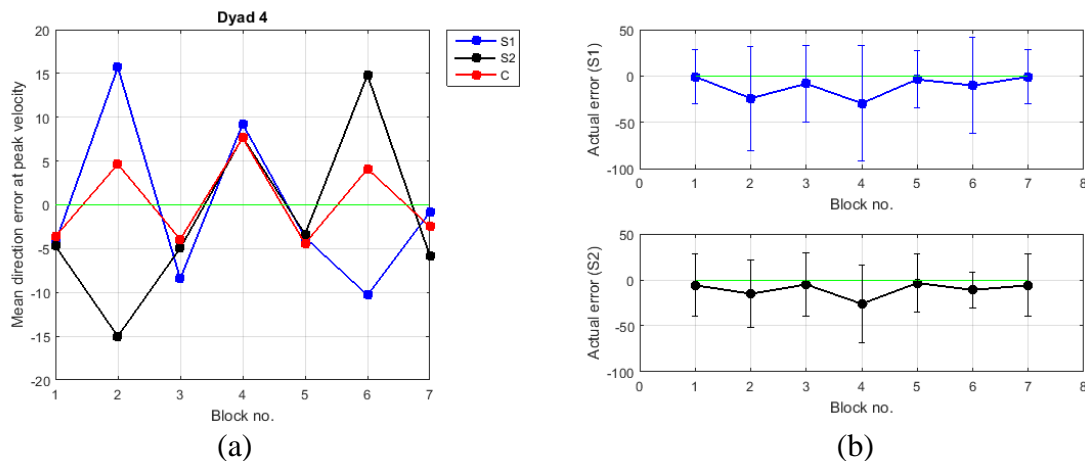


(a)                                    (b)

**Figure 3.12 Dyad 4** (a) Mean direction errors at peak velocities calculated from the data being displayed to the subjects during the game post-rotation (b) Mean direction errors at peak velocities calculated from the unaltered kinematic data; error bars depict one standard deviation for each block of 60 trials; (S1: -21.28±57.17, S2: -17.34±34.61)

Subjects in dyad 4 were able to de-adapt in the control blocks as S2 had small negative errors in blocks 1 and 7, whereas S1 had almost zero error. In blocks 3 and 5 both the subjects had small negative errors, which were not large enough to affect the cursor accuracy (Figure 3.12 (b)). Similar to dyad 3, S1 in dyad 4 had higher varibility in the values of mean direction error (S1: -10.97±59.80, S2: -10.42±39.29) as compared to S2.

De-adaptation was weak in dyad 5 as shown in figure 3.13 (a), with an average error of -15.4° for S1 and -11.2° for S2 in the control blocks. In terms of adapting to the visuomotor rotations in the test blocks, both subjects made corrective movements. In terms of mean direction error in the test blocks, S1 made larger corrective movements in block 2 compared to S2, whereas S2 compensated for the visuomotor rotation in block 6. However, both subjects compensated nearly equally in block 4 which was the block where both the subjects' coordinates were rotated during the game.

In terms of variability in the values of direction error in the three test blocks, S1 had a notably larger variability as compared to S2. Although the reason for such a large di-



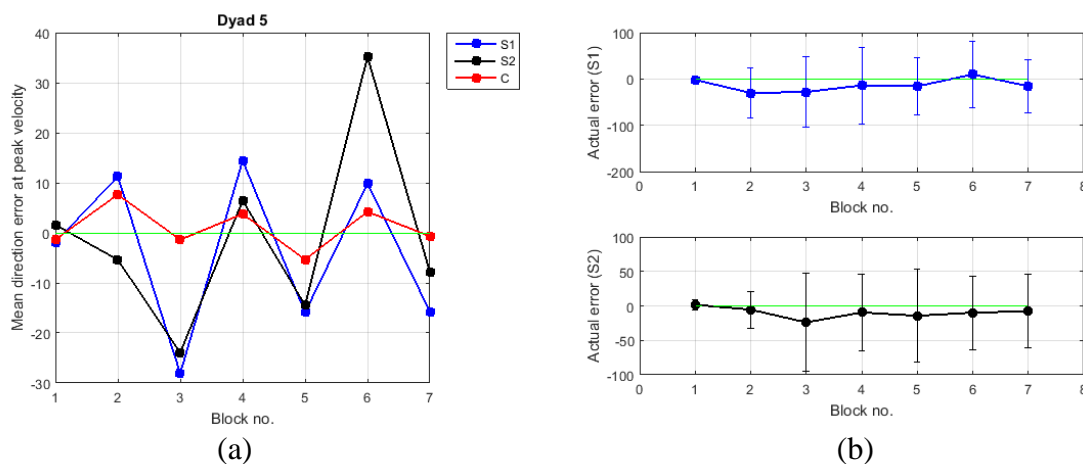(a)                                                    (b)

**Figure 3.13 Dyad 5** (a) Mean direction errors at peak velocities calculated from the data being displayed to the subjects during the game post-rotation (b) Mean direction errors at peak velocities calculated from the unaltered kinematic data; error bars depict one standard deviation for each block of 60 trials; (S1: -11.43±72.02, S2: -8.02±46.65)

fference is not clear, it is possible that the adaptation to the visuomotor rotation for S1 was weaker as compared to S2 in the three test blocks.

In dyad 6, the strategy used was similar to that used by dyads 3, 4 and 5 in which both the subjects moved in counterclockwise direction to varying degrees in order to counteract the visuomotor rotations collectively. The errors for the cursor in the test high blocks were higher than the previous and the subsequent control blocks. Subject S2 made small negative errors ($\leq 5°$) in CCW direction during the control blocks, but the cursor accuracy did not get affected because of small negative errors made by S1 (Figure 3.14)
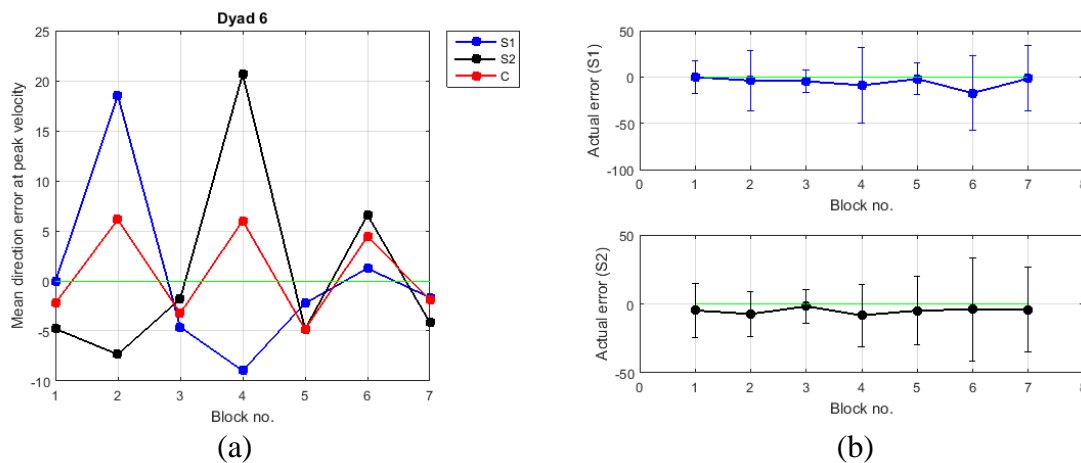


(a)                                                     (b)

**Figure 3.14 Dyad 6** (a) Mean direction errors at peak velocities calculated from the data being displayed to the subjects during the game post-rotation (b) Mean direction errors at peak velocities calculated from the unaltered kinematic data; error bars depict one standard deviation for each block of 60 trials; (S1: -10.09±37.96, S2: -6.55±26.93)

**3.4 DIRECTION ERROR AT ENDPOINT**

This analysis was done to see the whether the level of adaptation to visuomotor rotations increased, decreased or remained constant in subjects in the second half of reaching movement, i.e. after the point of peak velocity. This could give us information about the roles that each subject in a dyad played in maintaining the accuracy of their common cursor.

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As explained in section 3.2.1, due to the lack of feedback and any other information exchange, the endpoint for both the subjects did not occur at exactly the same sample during the continous sampling done for real time data collection. Similar to how the direction error at peak velocity was calculated, the direction error at endpoint for the cursor was calculated. Difference in the occurrence of endpoints was due to the differences in movement amplitudes as discussed in section 3.1.

For dyad 1, it was shown in the previous analysis (Figure 3.15) that irrespective of the visuomotor rotation, S2 was making nearly straight movements, evident from the small negative direction errors in the test blocks. As compared to the previous analysis, we did not notice any significant changes in the movement direction for S2, i.e. S2 made nealy straight movements on an average as compared to S1, which suggests a lack of cooperative effort (Figure 3.15 (b)). On the other hand, S1 made much larger corrective movements in the counterclockwise direction with an average direction error value of -29.08° for the three test blocks as compared to the much smaller value of -5.95° for S2 (Table 2). Varibility in the values of mean direction errors at endpoints was higher for S1 as compared to S2, (S1: -29.06±62.21, S2: -5.95±31.09), similar to that at peak velocity. This suggests that in an effort to maintain the cursor accuracy, S1 continued to have larger variability in the second half of movement.

As in the case of dyad 1, S1 in dyad 2 made large corrective movements in 2 out of 3 test blocks with an average counterclockwise deviation of -22.10° in the three test blocks as compared to -8.96° for S2. In block 6, S1 did not compensate for the visuomotor rotations and made nearly straight movements with an average deviation of around -0.24°.
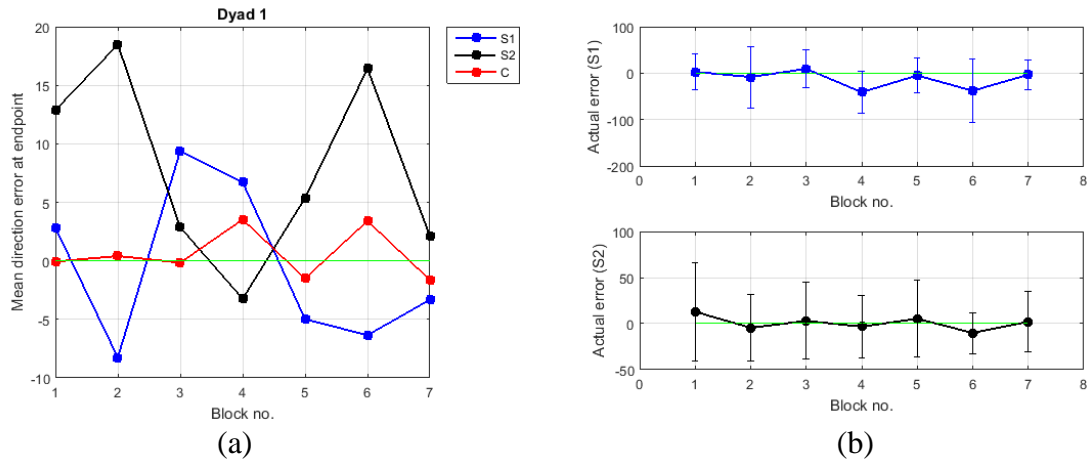
**Figure 3.15 Dyad 1** (a) Mean direction errors at endpoints calculated from the data being displayed to the subjects during the game post-rotation (b) Mean direction errors at endpoints calculated from the unaltered kinematic data; error bars depict one standard deviation for each block of 60 trials; (S1: -29.06±62.21, S2: -5.95±31.09)

However, S2 in dyad 2 had average direction error values of -10.49 and -11.44 in the first and second test blocks respectively, suggesting a better performance as compared to S2 in dyad 1 who had an average direction error of -10.13 in the third test block and small negative values in the other two test blocks.

Neither of the two subjects in dyad 2 (Figure 3.16) had difficulty in de-adapting to the visuomotor rotation. Average deviation for S1 in the control blocks was +1.06° and -3.92° for S2, thus the subjects were able to make straight movements in the control blocks.

Similar to dyad 1, none of the subjects in dyad 2 had any notable changes in the variability of direction errors from the point of peak velocity to the endpoint, although the varibility for S1 decreased more as compared to S2. Overall, subject S1 made larger corrective movements in terms of larger mean direction errors, both at points of peak velocities and at endpoints.

**Table 2** Mean direction errors at endpoints averaged across the three test blocks

| | | Dyads | | | | |
|----|--------|--------|--------|--------|--------|--------|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| S1 | -29.06 | -22.10 | -26.17 | -25.91 | -24.65 | -13.22 |
| S2 | -5.95 | -8.96 | -16.46 | -21.28 | -9.70 | -11.24 |



(a)                                  (b)

**Figure 3.16 Dyad 2** (a) Mean direction errors at endpoints calculated from the data being displayed to the subjects during the game post-rotation (b) Mean direction errors at endpoints calculated from the unaltered kinematic data; error bars depict one standard deviation for each block of 60 trials; (S1: -22.10±51.58, S2: -8.96±43.38)

In the case of dyad 3, both the subjects collaborated in a joint effort to complete the joint action task up to a certain level. However, the performance of the subjects in terms of the amount of cooperative effort was not maintained at the same level between the point of peak velocities and the endpoints. In the second haf of movement S1 made larger corrective movements as compared to S2, as evident from a larger shift in the values of mean direction error between the points of peak velocities and endpoints for S1 as compared to S2 (Table 1 and Table 2).
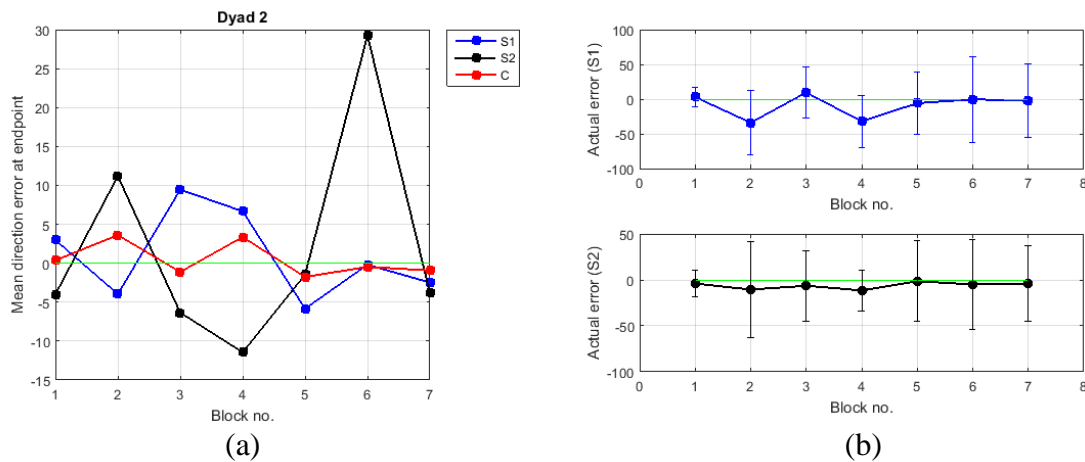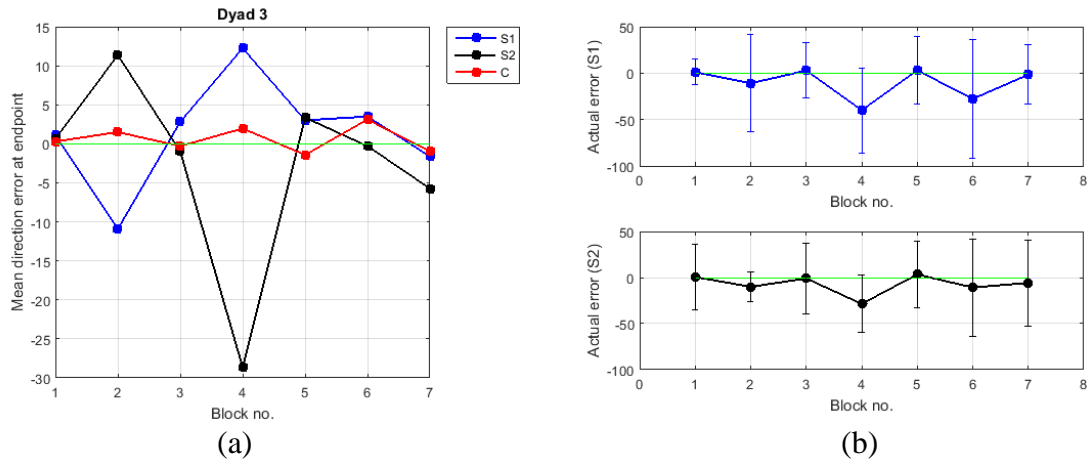
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**Figure 3.17 Dyad 3** (a) Mean direction errors at endpoints calculated from the data being displayed to the subjects during the game post-rotation (b) Mean direction errors at endpoints calculated from the unaltered kinematic data; error bars depict one standard deviation for each block of 60 trials; (S1: -26.17±55.68, S2: -16.46±37.29)

Mean direction error for S1 in the three test blocks was -26.17 and it was -16.46 for S2. Thus, as compared to dyads 1 and 2 in which one of the subject's contribution was significantly more than the other subject, in dyad3, although the subjects ensured a better effort but S2's contribution to the joint action task in dyad 3 was not remarkably similar to S1. The average direction error for the subjects in the control blocks was 1.33 for S1 and -0.66 for S2, thus ensuring straight reaching movements (Figure 3.17). There was no significant change in the varibility of mean direction error values between the point of peak velocities and endpoints for both S1 and S2 (S1: -26.17±55.68, S2: -16.46±37.29).

For dyad 4, the contribution from the subject S2 in terms of mean direction error was notably comparable to S1 unlike dyad 3. The average direction error at endpoints in the three test blocks for S1 was -25.91 and -21.28 for S2 (Figure 3.18). This suggests a better collaborative effort by the subjects to counteract the effects of visuomotor rotations in the test blocks. Also, in the control blocks, the average direction error for S1 was -2.36

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and -1.34 for S2, suggesting proper amount of de-adaptation following adaptation to the visuomotor rotation.

Similar to dyads 1, 2 and 3, subjects in dyad 4 had notable differences in the amount of variability in the mean direction error values at the endpoints, the subject S1 with higher value of mean direction error had higher variability as compared to S2 (S1: -25.91±57.33, S2: -21.28±34.07).

In dyad 5, subject S1 made most of the large corrective counterclockwise movements as evidenced by the mean direction endpoint error of -24.65 over the three test blocks, compared to a small value of -9.70 for S2. For the control blocks, the average direction error at endpoints for S1 and S2 in dyad 5 was high as compared to the subjects in other dyads (Figure 3.19).



(a)                                                   (b)

**Figure 3.18 Dyad 4** (a) Mean direction errors at endpoints calculated from the data being displayed to the subjects during the game post-rotation (b) Mean direction errors at endpoints calculated from the unaltered kinematic data; error bars depict one standard deviation for each block of 60 trials; (S1: -25.91±57.33, S2: -21.28±34.07)

The average value of these direction errors were -12.75 for S1 and -10.54 for S2 which suggests weaker de-adaptation in the control blocks following the test blocks.

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However, both the subjects had values close to 0 for the first block which was a control block, thus the dyad started the experimental session accurately. Apart from the notable differences in the values of mean direction errors at endpoints for S1 and S2 in dyad 5, both the subjects had large differences in the amount of variability in direction error values at endpoints (S1: -24.65±67.71, S2: -9.70±47.59).

Dyad 6 started accurately in the first block with both the subjects having direction errors close to 0 at the endpoints. In the subsequent test blocks, both the subjects shared the task nearly equally with an average direction error of -13.22 for S1 and -11.24 for S2 at the endpoints. Thus both the subjects compensated for the visuomotor rotations and thus were involved in a cooperative effort. For the control blocks, both the subjects in dyad 6 had low values of direction errors (Figure 3.20).



(a)                                                          (b)
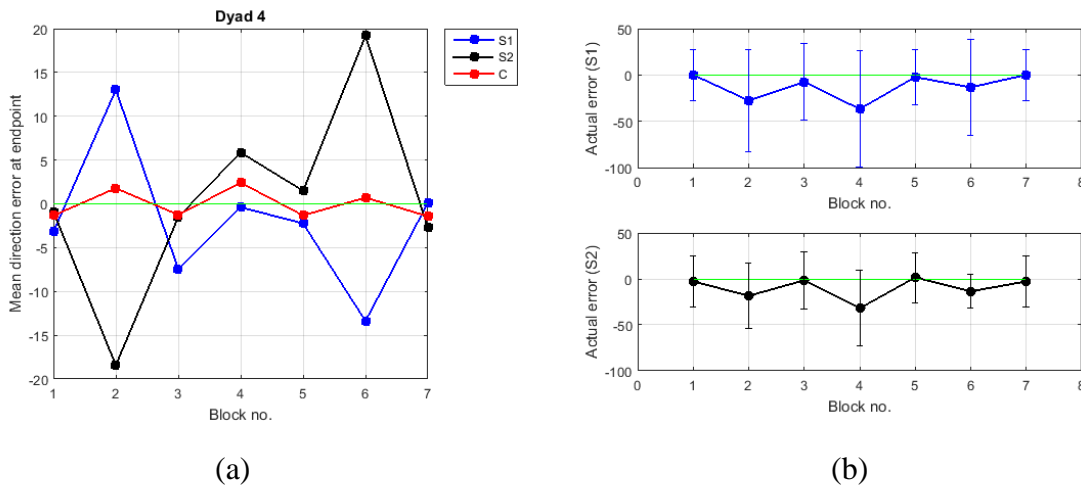
**Figure 3.19 Dyad 5** (a) Mean direction errors at endpoints calculated from the data being displayed to the subjects during the game post-rotation (b) Mean direction errors at endpoints calculated from the unaltered kinematic data; error bars depict one standard deviation for each block of 60 trials; (S1: -24.65±67.71, S2: -9.70±47.59)

With an average value of -1.49 for S1 and -0.36 for S2, both the subjects maintained nearly straight movements and thus showed strong de-adaptation to visuomotor rotations following the test blocks. Compared to all other dyads, subjects in dyad 6 had the lowest



(a)                                                                                      (b)
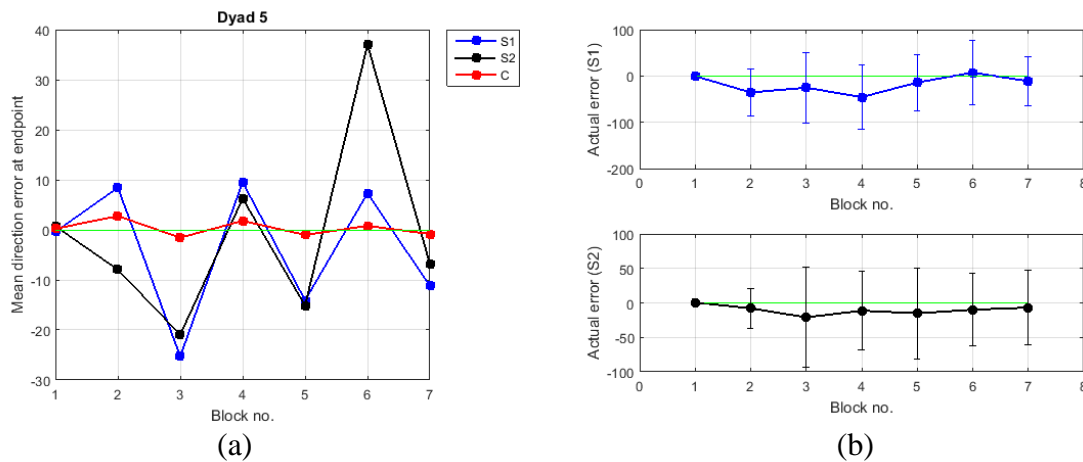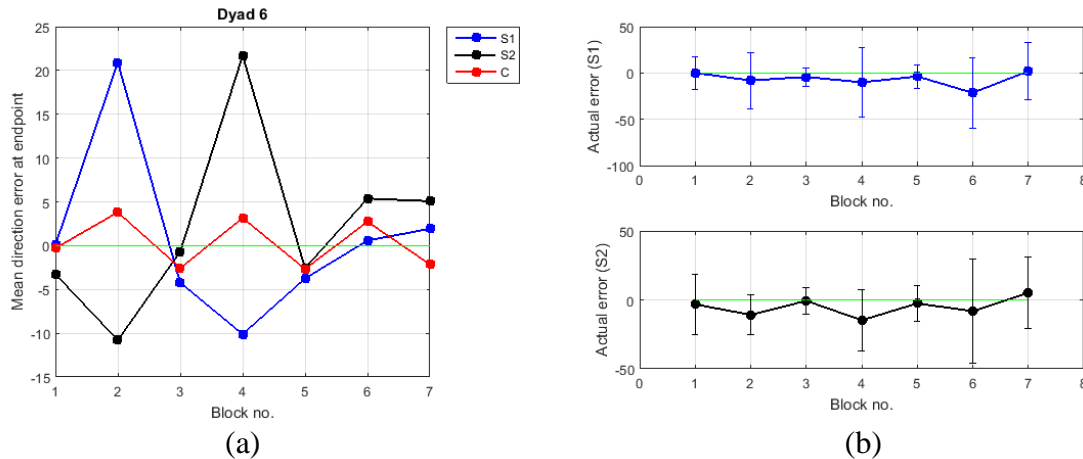
**Figure 3.20 Dyad 6** (a) Mean direction errors at endpoints calculated from the data being displayed to the subjects during the game post-rotation (b) Mean direction errors at endpoints calculated from the unaltered kinematic data; error bars depict one standard deviation for each block of 60 trials; (S1: -13.22±35.92, S2: -11.24±26.74)

variability in the values of mean direction errors both at the points of peak velocities and at endpoints. Moreover, this variability in the values of direction erros was comparable for S1 and S2, suggesting a cooperative effort.

## 3.5 TEMPORAL MEASURES OF COORIDINATION- MEAN MOVEMENT TIME

Unlike the notable differences obtained in the movement amplitude and direction for the subjects in the 4 out of 6 dyads, the mean movement times for the subjects in each of the six dyads were similar (Figure 3.21). This suggests that the subjects were able to coordinate the timing of their outward reaching movements to the peripheral targets. It is possible that the time constraint of 2 seconds given to them in order to complete one reaching movement to the peripheral target and back to the center target helped them to coordinate the timing of their movements.
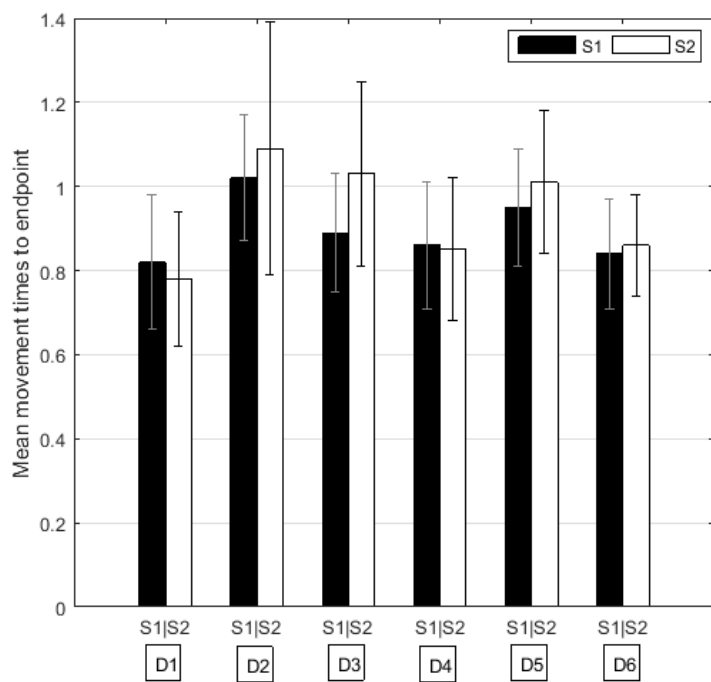
**Figure 3.21** Mean movement times for the six dyads found by averaging all the movement times for the 420 successful trials; Error Bars represent one standard deviation

CHAPTER 4

DISCUSSION AND FUTURE WORK

**4.1 DISCUSSION**

The aim of this study was to analyze the behavior of the subjects and the strategies that they used to perform a virtual reality task, devoid of feedback regarding the partner. Since the only information that the subjects had regarding their partner was the common cursor feedback, we were interested to see whether the subjects modulated their own actions according to the actions of their partner or if they performed in a manner irrespective of the actions of their partner. Accordingly, we analyzed the movement characteristics of the partners in each dyad in terms of both amplitude and direction in order to compare the relative contribution of the two subjects in maintaining the accuracy of the cursor movements. Our findings suggests that in 4 out of 6 dyads, one of the subjects made larger efforts in terms of his or her own adaptation to the task and compensation for the lack of partner's efforts. In the remaining two dyads, both the subjects had notably comparable efforts and thus were involved in a cooperative strategy.

Previous studies on visuomotor adaptation with individual subjects suggests that online motor corrections do not facilitate visuomotor adaptation (Shabbott and Sainburg 2010), i.e., correcting errors during movement doesn't interfere with the amount of adaptation to the visuomotor rotation. The study showed a similar level of visuomotor adaptation in two groups in which the subjects either did or did not correct errors during movement. However, in a case of joint action between two individuals, online error correction has a major role in adapting to the visuomotor rotation since the errors made by one subject need to be corrected by the other subject during the movement in order to

ensure accurate performance of the dyad. In our study, we tested the coordination between the subjects through visuomotor perturbations provided to either one or both the subjects' movement direction. To derive a complete picture of the adaptation process, we started by analyzing the subjects' workspace in terms of movement amplitudes, i.e. whether either one or both the subjects made movements similar to the actual target distance. Mainly, our objective was to see whether both the subjects in a dyad followed a similar strategy in terms of path length while reaching to one of the four targets.

Results obtained for four out of six dyads (1, 2, 3 and 5), suggests that one of the subjects made significantly larger movements in order to compensate for the much smaller movements of their partner and thus our results point towards compensatory strategies that could exist between partners in the absence of feedback. To ensure that the differences obtained in the movement amplitudes for the subjects were not due to disproportionate mapping of subjects' 3D coordinates to the common 2D game coordinates during calibration, we re-examined the calibration procedure and found no inconsistencies in our procedure. To further validate the findings regarding the movement amplitude, we analyzed the amplitude of mean peak velocities for each of these subjects and their partners and found differences that were nearly proportional to the difference in movement amplitudes, i.e. the subject with a larger movement amplitude had higher peaks of velocity.

During the above analysis, for some dyads, we also acknowledged the possibility of cooperative strategies at certain instances in terms of simultaneous adjustments to the movement amplitudes. In dyads 2, 3 and 5, where the value of ratio (r), defined in section 2.5.2.1, increased for S1 from blocks one to three, it decreased for S2. Overall, this suggests that the co-actors who had significantly different movement amplitudes were still able to

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adjust their movements according to the partner in the absence of feedback regarding the partner. Ruys and Aarts found that in interdependent (competitive) situations, the co-actors develop shared representations of each other and thus develop the ability to attend to each other's intentions (Ruys and Aarts 2010). In our task, although the participants were independently performing their part of the task without any feedback regarding the partner, they were still required to attend to each other's intentions with the help of common cursor feedback to maintain the cursor's accuracy and there was an involvement of interdependency between the subjects for completing the virtual reality task.

In our next analyses, adaptation to visuomotor rotation in terms of direction error, was analyzed in two halves of the reaching movement, i.e. in the first half from the starting point to the point of peak velocity and in the second half from the point of peak velocity to the endpoint. Interestingly, subjects in the four dyads (1, 2, 3 and 5) which had differences in the movement amplitudes also had notable differences in the amount of visuomotor rotation. In all these dyads, the subject S1 which had larger path lengths as compared to S2, adapted better and absorbed the majority of visuomotor rotation by making larger corrective movements in the direction opposite to visuomotor rotation, as seen from the larger negative values of mean direction errors as compared to their respective partners. Evidently, in these dyads, one of the subjects did not make enough effort to coordinate and relied on their partner for maintaining the accuracy of the cursor both in terms of direction and distance. This is indicative of a phenomenon called 'social loafing' in which "an individual has a tendency to expend less effort when working collectively than when working individually" (Karau and Williams 1993). According to this meta-analytic review, there is a lack of motivation in the subjects to contribute when the outcomes of the task are

not valued. Factors like less or no payment for the task, lack of self-evaluation information and low intrinsic value of the task contribute to the degrading performance of individuals in a collaborative effort (Karau and Williams 1993).

Since we did not pay the subjects for their participation and there was no separate 'knowledge of results' after the end of the trials for the subjects, there is a possibility of contribution of such factors to the slacking performance of one of the subjects in the four dyads. Another possibility is that the amount of time taken by the dyads to complete the seven blocks of trials exceeded their expected time tolerance and might have further added to their decreasing contribution to the task.

Results obtained for dyads 4 and 6 suggest that the contribution of the subjects was comparable with their respective partners. The subjects had comparable performance both in terms of maintaining a nearly constant average path length over the blocks and making similar adjustments to the movement direction. In situations where continuous feedback regarding the partner's actions is not available, reducing the variability of their own actions can help the subjects to be as predictable as possible to the partner which further leads to a successful coordination through cooperation (Vesper et al. 2011). Stated differently, in terms of our joint action task, making nearly constant movements might have helped the subjects to predict their partner's actions because any variability observed in the common cursor's movements would have resulted from the inconsistencies in their partner's movements. This points towards a cooperative strategy arising in dyads 4 and 6 where the subjects contributed to the task by performing in a manner consistent with that of their partner's. Additionally, such cooperative strategy turned out to be beneficial for both the dyads as none of the subjects had to expend extra efforts in order to compensate for the

partner's lack of contribution. Overall, our findings suggests that even in the absence of feedback, subjects can learn to cooperate over the course of the joint action task by stabilizing their own performance and maintaining joint attention with their partner.

## 4.2 FUTURE WORK

In this study, we studied the interaction scenarios arising between individuals who collaborated in the absence of feedback. We used the direction and amplitude of the subjects' movements to measure the amount of cooperation that existed between the subjects for completing the joint action task. For future work on joint actions in the absence of feedback, developing other spatial and temporal measures could help in strategy classification. However, keeping in mind the variability of human nature in different contexts and with different individuals, defining specific measures of coordination in human joint actions remains quite challenging.

Moreover, efforts should be made to re-create real world situations as closely as possible in the laboratory for studying joint actions so that external factors that affect the performance in a joint action could be included in the paradigm. Although the design of our joint action task was sufficient to incorporate and study simultaneous efforts of two individuals, future work could consider designing tasks that could further lower down the chances of subjects reducing the level of their performance over time. It is possible that in our joint action task, the weaker performance of one of the subjects in 4 out of 6 dyads was due to the fact that subjects were required to make fast movements in a complete 3D workspace, while holding their hand against gravity. Apart from creating a comfortable working environment for the subjects, some other factors including availability of self-evaluation information about individual performance after trials, providing proper

compensation to the subjects and finding ways to reduce the total session time could help in enhancing the performance level of the individuals. Making the task more interesting by introducing rewards for successful trials might encourage the subjects to maintain a high level of contribution, especially in conditions where the individuals performing together are socially unacquainted with each other, as in the case of our joint action task.

If possible, the neural recordings from the brains of participating individuals should also be captured along with behavioral data to develop a better understanding of the mechanisms underlying a joint effort since activation patterns in different parts of the brain are associated with different mental processing and can provide information that is unavailable from the behavioral analysis. In an EEG Hyperscanning study done by Astolfi and colleagues, simultaneous neural recordings were done from the subjects in each dyad involved in a cooperative task. The results of this study found out significant differences in terms of inter-brain functional causal links, when comparing the conditions where the subjects were actually involved in a cooperative task with their partners or a condition where they asked to perform with a computer, while the responses were actually coming from a human partner (Astolfi et al. 2014). Such an analysis could be included in the future work of joint actions to find out the neural substrates of performance in a joint action task where no feedback regarding the partner's part of the task is available and thus can lead to important conclusions regarding the roles of the interacting partners in attaining the common goal.

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