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Skill Learning via Haptic Interaction

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This thesis is dedicated to my lovely family
for their constant inspiration and encouragement.

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Abstract

Humans need to interact with others and coordinate their actions with them in some activities requiring cooperation such as team sports or ensemble musical performance. In team sports, coordinated behaviours emerge based on the interpersonal synergies between players under the supervision of a coach. Successful ensemble musical performance requires each player to adjust the timing of his or her own tone onsets. Success in a cooperative task depends on adaptation to unknown dynamics in the interacting environment (e.g. environmental or partner dynamics). This PhD thesis aims to address the issue of instability arising from dual dynamics (i.e. dual instability due to environmental and partner dynamics). We developed a cooperative motor task in which a virtual mass was connected to two cursors controlled by subjects with a joystick or a robotic arm. Humans have a natural ability to interact with others by auditory, visual or haptic feedback. First, skill learning and adaptability were assessed through interaction with an artificial agent model (i.e. expert) in the absence of haptic feedback. Secondly, haptic feedback was integrated into the experimental paradigm, and adaptability was investigated in human-human interaction. How can humans deal with dual instability caused by partner and environmental dynamics within a cooperative motor task? We hypothesized that separation of dual dynamics would result in skill learning. Lastly, an EEG-hyperscanning study was performed to identify the neural signatures of successful mutual skill learning. The pilot EEG study showed the emergence of coordinated behaviour, resulting in mutual skill learning.

Keywords: motor skill, skill learning, adaptability, dual instability, human-human interaction, human-agent interaction, hyperscanning.

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Chapter 1

Introduction

As social beings, humans need to learn a variety of motor skills to be used in many aspects of life such as at home, school, work or sport. How a parent, teacher, athletic trainer or physical therapist facilitates the learning process has been a growing interest to research with the increase in the studies about social interaction. Social interaction, which is a process including reciprocal action and reaction between two or more people [1], is fundamental to acquire new skills in a changing world [2].

Visual [3], auditory [4, 5], haptic feedback [6, 7] or a combination of them [8] can make available to learn new skill sets through the interaction with someone (e.g. teacher or trainer). The recent technological developments facilitated the usage of robotic haptic interfaces [9–11] to provide haptic interaction between two person. Previously it has been found that a paired performance is more advantageous than an individual one to improve motor task performance (even interacting with a worse partner) [10].

Over the last few years, a considerable amount of studies have focused on the effect of the roles on dyadic performances such as leader-follower [12, 13] or novice-expert [11, 14]. For instance, in ballroom dances the dyadic performance is closely associated with the coordination dynamics of the follower and leader. The dyadic interaction may give an opportunity to learn dance from the dance trainer. In rehabilitation, physical therapist (expert) assists the patient (novice) to (re)learn motor skills. Previous studies [10, 11, 14] outlined that novice-to-novice interactions induced better skill learning than novice-to-expert interactions.

While learning skills through interaction with others, humans can face a dual instability arising from the environment and the interaction with a partner. The research to date focused on skill learning mostly through adaptation to environmental dynamics by employing virtual force fields in reaching tasks [11, 15] or visuomotor rotation task [10,16]. However, to our knowledge, no study has considered adaptation to an interacting person under unknown environmental dynamics. It is important to note that performance improvement in a cooperative task relies on adaptation to the changing conditions in the interacting environment [17] (e.g. environmental or partner dynamics). For instance, in team sport activities, such as in a basketball match, the players in a team must adapt to their teammates to play coherently as a part of a team as well the players in the opposite team and the environmental conditions to win the match. In paired skating, an ice skater must adapt to the environmental changes and the partner's motion as well to move together on the ice ground.

The PhD project aims to investigate the issue of dual instability in the context of motor learning paradigm. To this aim, we designed a cooperative motor task based on the recent study [11].

In the first study presented in Chapter 3, we hypothesized that more experience in a cooperative visuo-motor task would lead to higher adaptation to other person (adaptability). To investigate the effect of initial skill level of the interacting person, experimental protocol was set in two groups: Novice-Novice (N-N) and Novice-Expert (Novice-Expert). Here, novice refers to a participant having no previous experience in the task. The aim of this study was to develop an artificial agent model representing guidance as an expert. The results suggested that practicing with a novice was more advantageous than training with an expert agent for the adaptability. Note that there was no applied task-related haptic feedback while the subjects were interacting with each other.

In the second study presented in Chapter 4, we suggested that motor skill learning can happen only in the presence of adaptability. The results were consistent with the first study (Chapter 3) even though there was an additional task-related force in addition to visual feedback. The studies stated that novice-to-novice interactions induced higher adaptability, leading to skill learning. However, still, much less was known about dual instability.

To address an issue of how to deal with dual instability, in the third study presented in Chapter 5, we hypothesized that separation of dual dynamics (partner and environmental dynamics) would result in skill learning. It is known that the visual perception of movement is crucial to perform cooperative tasks [18], On the other hand, the haptic perception has been proposed as the most direct interaction form in motor tasks [8]. Considering them, the movement-related visual feedback was removed from the experimental paradigm. The findings showed that adaptation to dual dynamics in a sequence (i.e. sequential learning) enhanced motor performance in a cooperative haptic motor task.

Last study presented in Chapter 6 has been devised to investigate the neural signatures of the mutual skill learning. EEG hyperscanning technique allows us to observe the neural signatures of two-people simultaneously [19]. It has been found that mutual adaptation resulted in interactional synchrony [20]. Thus, we expected to observe inter-brain synchrony in case of skill learning through adaptation to unknown dynamics.

1.1 Aims

The aims of this thesis are:

1. To understand the importance of haptic channel on a cooperative task
2. To investigate necessary conditions for the best motor learning
3. To find optimal trade-off between three factors for the best motor learning
   (i) Exploration on one's own
   (ii) Exploration with an expert
   (iii) Adaptation to others
4. To investigate the issue of dual instability (i.e. discriminating unknown environmental and partner dynamics)
5. To characterize the haptic coupling (van der Wel et al. [6] suggested that haptically linked dyads create haptic communication channels by applying force to an object simultaneously.)
6. To identify neuromarkers of skill learning using EEG-hyperscanning method

1.2 Thesis Structure

The three main chapters 3 to 5 of this thesis are written in the form of manuscripts which are either published or submitted to the academic peer-reviewed journals. The papers in chapters 3 and 4 are published in Advanced Robotics and Frontiers in Neurorobotics, respectively. The manuscript in chapter 5 has been submitted to Scientific Reports. The papers are written according to the guidelines and requirements of the respective journals, and so there may be variations in the format of the papers.

The author of this thesis, Ozge Ozlem Saracbasi (OOS), is the second author of the journal paper presented in chapter 3, after Kotaro Nishimura. OOS discussed the results with the co-authors, Toshiyuki Kondo and Yoshikatsu Hayashi, and contributed editing of the manuscript, mostly Introduction and Discussion sections. OOS is the first author of the journal papers presented in the chapter 4 and 5. OOS performed the literature review, developed the experimental setup (see Appendix A), did participant experiments, analyzed the data set, produced all corresponding figures, and discussed the results with the co-authors. The co-authors are Yoshikatsu Hayashi, William Harwin and Toshiyuki Kondo, who are the supervisors of the author of this thesis, Ozge Ozlem Saracbasi.

Chapter 2 presents a comprehensive literature review to gain a better understanding of the previous studies in the field of motor learning and adaptability, haptic interaction, internal model and EEG hyperscanning. Chapter 3 investigates skill learning through adaptation to others (novice or artificial agent model) by employing a cooperative visuo-motor task. Chapter 4 characterizes the trade-off between three factors for the best motor learning: exploration on one's own, exploitation with the expert and adaptation to others. Chapter 5 addresses an issue of dual instability arising from environmental and partner dynamics. Chapter 6 explores the neural signatures of mutual skill learning through haptic interaction. Finally, Chapter 7 provides overall insight into all studies performed during the PhD.

Chapter 2

Literature Review

The PhD project lies at the intersection of four research themes. Thus, this chapter is divided into four sections that summarise these research themes driving this thesis: (1) Motor learning and adaptability (2) Haptic interaction (3) Internal model and (4) EEG Hyperscanning.

Success in a cooperative motor task depends on adaptation to unknown dynamics in the interacting environment (e.g. environmental or partner dynamics) [21]. In this PhD project, we, first, aimed to research how the adaptability to others can emerge through the mutual motor learning experience (Chapter 3), and then to study the relationship between skill learning and adaptability to others (Chapter 4). Following these studies, we hypothesized that separation of dual unknown dynamics in the interacting environment would result in skill learning (Chapter 5). In this PhD project, the main research theme was motor learning and adaptability, so the first section will introduce motor learning and adaptability. The second section will give a review of relevant publications on haptic interaction, being the communication channel between the paired participants in all these studies. Our findings suggest that an internal model of the partner is necessary to simulate the motion of the partner in response to which one can perform an action. Thus, the third section will give a brief introduction to internal model to explain the findings more clearly. Lastly, a pilot EEG-hyperscanning study (Chapter 6) was performed to identify the neural signatures of the successful mutual skill learning. Therefore, EEG Hyperscanning will be introduced in the fourth section.

2.1 Motor Learning and Adaptability

Motor learning can be defined as a set of internal processes, which occurs in the brain with practice and leads to learning a new motor skill or relearning a motor skill after stroke [21, 22]. Motor skill refers to a specific goal to achieve. Motor skill acquisition follows three stages: cognitive, associative and autonomous stages, respectively [21, 23–25]. First, in the cognitive stage called attention-demanding phase [8], a novice (i.e. person having no experience with the task) learns how to perform a motor task based on self-observation or instructions by an expert. Learners show a distinctive performance improvement in this stage. After understanding the motor task, learners execute the task to increase accuracy and fluency [26]. In associative stage, the intermediate stage, learners spend much more time to improve their performance compared to the cognitive phase. In conjunction with cognitive and associative stages, learners start to execute the task automatically. This stage is called autonomous stage, in which learners execute the task with maximum accuracy and minimum energy. Movements are performed with reduced mental effort as well [27]. Motor skill acquisition allows a novice person to become an expert (i.e. skilled performer) in a variety of motor skills such as musical skills, sports or dancing.

In recent years, there has been a great deal of interest in investigating dyadic physical interaction in skill learning process. To investigate dyadic physical interaction, van der Wel et al. [6] designed a cooperative task in which subjects were asked to balance a stick between two targets individually or with a haptically interacting partner. The results suggested that even though both interacting two-person (pair) and individuals completed the task approximately in the same amount of time, pairs amplified their forces, which pointing the presence of a haptic information channel. In another study, Ganesh et al. [10] designed a system in which two-person tracked the same continuously moving target presented on the screen by controlling the handles of dual-robot interface. Within the scope of this experimental paradigm, physical interaction was provided by connecting the handles of robotic interfaces with a virtual elastic band such that each subject was pulled towards the partner. However, the subjects were unaware of the physical interaction, and also did not receive visual information of their partner's movement. In a sense, the experimental task would not be thought as a cooperative task. Nevertheless, the findings showed that paired performance was more advantageous than the individual one to learn the task. Physical interaction enabled individuals to learn the motor task regardless of their partner's performance (even with a partner having worse performance). Another study [28] showed that collective physical interaction resulted in performance improvement such that the performance improvement was higher in tetrads than dyads in a tracking task.

Motor learning is correlated with adaptation to unknown dynamics in the changing environment [15,21,29]. Herein, adaptation can be defined as a form of learning, being examined with performance improvement in response to changing conditions [30]. For instance, in sport activities such as tennis, the changing environment consists of the tennis ball and the other player at the opposing side of the net. In the case of physical human-human interaction which facilitates motor learning, learners can be faced with dual instability arising from the interaction with others (e.g. player or trainer in sport activities) and the changing environment (e.g. the trajectory of the tennis ball) [31].

In the recent years, a number of studies [32, 33] identified different control strategies to accomplish complex motor tasks: stiffness stabilization strategy (SSS) requiring high effort and positional stabilization strategy (PSS) requiring low effort. Zenzeri et al. [34] showed the possibility of strategy switching in well-trained subjects (experts). They, also, found performance improvement in both strategies due to training, and stated the simplicity of the SSS strategy. Saha and Morasso [33] characterized the behavior of naive subjects particularly in the initial phase of learning. In addition, De Santis et al. [2] investigated the effectiveness of the strategies required to stabilize a virtual mass within a circular target under the force field. The results showed that the paired performance was tied to adaptation to instability arising from the interaction with a partner and changing environmental conditions. The study, also, indicated the minimization of effort in the dyadic performance. Afterward, De Santis et al. [31] stated that the experts and pairs applied similar effort to execute the task.

Numerous studies have examined the effects of the roles on skill learning such as novice-expert [11, 14] or leader-follower [12]. For instance, in rehabilitation, a physical therapist and a patient take the role of leader and follower, such that the patient follows the physical therapist's instructions or movements during the treatment, which results in motor (re)learning. From another perspective, the therapist and patient are considered an expert and a novice such that the therapist guides the patient throughout the treatment. Ganesh et al. [10] stated that the performance improvement was more obvious while learning skills with a person having same skill level (novice-novice learning). Afterward, Avila-Mireles et al. [35] designed a virtual tool in which a virtual mass was connected to the handles of haptic robots [9] through two non-linear virtual springs. They highlighted that the initial skill level of partner had a strong impact on skill learning. Following this study, they found that having trained with an expert led to the best performance. However,in the absence of the expert, the novices trained with the expert could not perform the task individually if they did not have any prior experience with the task dynamics [11]. The study, also, emphasized the importance of exploration of unknown dynamics to utilize the motor skills individually. Using the same experimental setup, Galofaro et al. [36] aimed to find the motor skill learning algorithm. They found that the novice who applied insufficient effort could exploit the expert (partner dynamics), however, not the environment. In addition, the recent study conducted by Kager et al. [14] indicated that novice-novice learning might be more advantageous for tracing accuracy, and individual practice for the speed increase.

Error-based paradigms including force fields [11, 15] and rotations [10, 14] have been used to investigate skill learning [30]. Adaptation to force field was examined in the context of goal-directed reaching movements [37]. Table C.1 describes the previous studies on skill learning with their results.

Skilled motor behavior comes from action-perception coupling in which perceived sensory information allows for accurate action [21]. Action-perception coupling could rely on visual, auditory, or haptic information. For example, in table tennis, auditory perception is important to perceive ball bouncing on the racket and table. Visual perception has an impact on performance as well, such that players act depending on perceived information of ball position [8].

2.2 Haptic Interaction

Humans are able to adjust their own behaviour based on the sensory feedback [13]. For example, one can notice an obstacle in the way with visual feedback. Multi-sensory feedback integrating visual and haptic information provides to carry a heavy sofa with someone. Skilled behaviour requires the efficient and effective sensory information to learn the key features of the task such as the shape of ball and the environmental factors affecting the ball movement (e.g. wind or court surface) in tennis [17, 38]. Following three-stage model of motor learning process, error correction mechanisms are improved by utilizing sensory afferences such as auditory, visual [3] or haptic feedback in associative stage [8].

In daily life, the integration of information from multiple senses, including visual–auditory [39, 40] or visual-haptic [41] integration is fundamental to interact with the environment [42] and learn a variety of skills. Visuo-haptic perception has a strong impact on education, sport and rehabilitation [12], providing motor skill (re)learning. For instance, visuo-haptic feedback has been found more effective than the visual feedback to teach handwriting [43]. Technological developments made available to use robotic devices to provide haptic feedback in skill training [8]. Feygin et al. [44]

investigated haptic training by using a robotic device, and found that haptic training improved timing of motor performance regardless of visual feedback. Afterwards, Patton and Mussa-Ivaldi [45] investigated adaptation to force fields by employing a two-degree-of-freedom manipulandum.

To date, numerous studies have attempted to research the impact of haptic interaction on motor learning by employing a joint task. Herein, joint task can be defined as an action in which two or more people coordinate their actions for a common goal. The success in joint action relies on the ability to infer the common goal by interpreting the cues about the other's action and environment [46, 47]. Reed et al. [48] identified the difference force as a communication channel between two persons in the context of dyadic physical communication, which inducing the impact of haptic channel on physically coupled joint actions. Van der Wel et al. [6] found that dyads amplified their forces to construct a haptic information channel, leading to smooth interpersonal coordination. In addition, some of previous studies [2, 31, 49] outlined the importance of mutual haptic feedback for the efficient process of intention integration between two person. In contrast with these studies, Takagi et al. [50] demonstrated that rigidly coupled pairs did not change their motion plans and coordinate their movement during a joint reaching task. Physical interaction, also, enabled interacting individuals to improve their own motor performance regardless of their partner's performance [10]. Also, dyads benefited from physical interaction to estimate their partner's goal [51]. In particular, in visuo-haptic tasks, dyads extracted their partner's target using the haptic interaction and combined it with visual information [51, 52].

The other important point to be considered is the coupling strength in haptic interaction, which plays a key role to sense the cues in the interacting environment. Takagi et al. [52] found that haptic interaction enabled to estimate the other's movement regardless of the coupling strength. Meanwhile, a stronger coupling enhanced the process of intention integration whereas a softer coupling deteriorated the process.

Sensory feedback refers to the perceived information as a result of task performance [22], which is important to shape the internal model of dynamics in the joint task [11], and update internal representations in response to changing conditions [53]. Utilizing the sensory information, Central Nervous System (CNS) [54] can generate motor commands within the social interaction in which people act or react in response to other's behaviour [55].

2.3 Internal Model

In motor learning, humans need internal models [56] to adapt to changing conditions and predict others' motion. Internal models predict external forces based on experience, which enables better motor performance with practice. Also, internal models enable to model dyadic interactions. Internal model can be defined as an approximation of the unknown dynamics in the task [15, 57] and classified as forward and inverse internal model. Forward internal models represent the future states of a process relying on given sensory and motor inputs, and inverse internal models compute motor output in the desired time point [46]. The forward model is represented by the computations, which start with a copy of the motor command and end with a prediction of the estimated position. On the other hand, the inverse internal model computes the motor command to be sent to the body by utilizing the desired sensory consequence and the current state of the body and environment [58]. Action perception relies on forward internal models, in which actions are generated based on the sensory consequences of individual's own and partner's actions [54]. Internal models can be damaged from stroke or motor deficits.

In the case of physical human-human interaction, humans can be faced with the issue of dual instability arising from two unknown dynamics (i.e. partner and environmental dynamics) [31]. Learning the internal model of the unknown dynamics allows for motor skill learning [22, 59]. Although motor learning involves multiple processes, error-based motor learning paradigms can be investigated in terms of adaptation, which refers to update an internal model. When acting in an environment with unknown dynamics, the internal model is updated to reflect the dynamics of the new environment [60]. Thus, it is important to form an internal model to adapt to unknown dynamics such as force field in the environment or partner dynamics [15, 61]. A state-space model (Fig.2.1) allows to describe the process of internal model acquisition [60].

Internal models are neural mechanisms which can mimic the characteristics of the motor apparatus such as a robot manipulandum [62]. Central Nervous System (CNS) forms the internal models of unknown dynamics in the interacting environment [29].

2.4 EEG Hyperscanning

In a joint task where a person interact with others, perceived information is transferred among the interacting people's brains [63]. Hyperscanning (i.e. two-person neurosicence [64] or dual scanning [65]) is a neuroimaging technique which enables

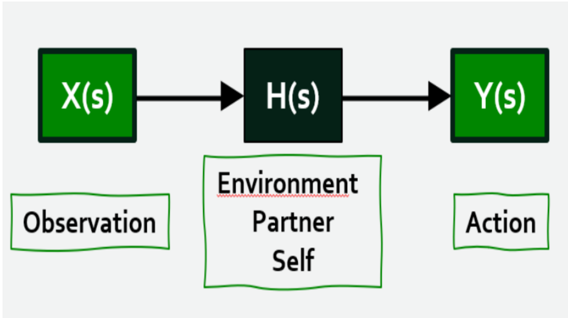

Figure 2.1: A state-space model representing the internal behaviour of the system allows us to understand the inner working of the system.

to explore neural activities of two interacting persons by recording brain activities simultaneously [20, 66–68].

To date, several hyperscanning studies have been carried out to investigate neural activity in social interactions including musical performance [69–71], motor tasks [1,20] and speech [72]. Hyperscanning was also utilized to study the social interaction between mother and children [73,74], teacher-student [75], the members of an aircraft crew during the flight [76], and the roles during the interaction such as leader-follower [69, 77–79], actor-observer [53], model-imitator [20] and speaker-listener [80, 81].

In the last decade, the most popular neuroimaging techniques [82, 83] used to investigate neural mechanism of social interactions are functional magnetic resonance imaging (fMRI) [66,84–86], functional near-infrared spectroscopy (fNIRS) [74,75,87], Electroencephalography (EEG) [1, 19, 20, 69–71, 77, 88–90] and Magnetoencephalography (MEG) [73,78,81,91,92]. Although the spatial resolution of EEG remains lower than fNIRS, fMRI and MEG, EEG has higher temporal resolution when compared with fNIRS [93]. In addition, EEG is less expensive and portable, which enables to design experimental setup in a more natural manner [87, 91, 94]. In spite of the low mobility, the first hyperscanning study [66] was performed using Functional magnetic resonance imaging (fMRI). Even though fMRI was the first neuroimaging technique used in hyperscanning studies, EEG has been most common technique due to higher temporal resolution and higher mobility with the improvements in EEG equipments [82]. The high temporal resolution is important to analyse brain activity more precisely. EEG records the real-time electrical activity on the scalp, which allows for brain activity analysis relying on voltage fluctuations [95, 96].

EEG hyperscanning has been used in a variety of experimental paradigms, including finger-tapping tasks [1, 79, 97], card games [88, 90], game theory [19], imitation [20] and musical performances [69–71, 98, 99].

To identify neural correlates of synchronized and unsynchronized behaviour, Tognoli and colleagues [1] designed a rhythmic finger-tapping task with or without vision, in which trials were classified into three categories: unsynchronized, transiently synchronized and fully synchronized. Considering spectral analysis of EEG activity, they found three distinct brain rhythms within the range 7.5-13 Hz; in particular, alpha rhythm with the mean frequency of 10.61 Hz, mu rhythm with 9.63 Hz and phi complex ranging from 9.2 and 11.5 Hz. They identified the phi complex with two oscillatory components: Phi1 and Phi2 rhythm found above right centro-parietal cortex. The study showed that unsynchronized behaviour resulted in an increase in Phi1 power in the right centro-parietal region, and a decrease in the left centro-parietal cortex. On the other side, synchronized behaviour led to an increase in Phi2 power in the right centro-parietal region. Namely, they underlined that an increase of Phi1 and Phi2 identifies independent and coordinated behaviour, respectively. Additionally, the power of mu in the Rolandic region and alpha in the posterior region decreased by visual stimulation. In this study [1], they emphasized that although both mu and phi rhythm belong to human mirror neuron system, alpha-mu is associated with functioning, and phi is importance of characterization of individual behaviour. To conclude, Tognolli defined the phi complex as a robust neuromarker to discriminate synchronized and unsynchronized behaviour by analysing intra-brain dynamics, not inter-brain. By using the same dual-EEG system with in-phase and anti-phase condition, Naemm et al. (2012) [97] found similar results such that intra-brain synchronization was observed in mu frequency band (10-12 Hz) in right centro-parietal regions. Also, they reported that mu was activated while differentiating finger movements during in-phase or anti-phase condition.

On the contrary, Dumas et al. [20] identified the alpha-mu rhythm (9.2-11.5 Hz) as a robust neuromarker of synchronized behaviour using inter-brain statistical analysis within the centroparietal regions of two interacting person. In this study, interactional synchrony was measured in two experimental conditions including spontaneous imitation and induced imitation of hand movements. In the spontaneous imitation, participants were asked to imitate their partner's hand movement as shown in the screen whenever they wanted. In the induced imitation, participants were asked to imitate their partner's hand movement as shown in the screen when the experimenter asked to imitate. Examining phase synchronization between two brains (e.g. model-imitator), synchronization was found in alpha-mu band between right centro-parietal regions, beta band between central and right parieto-occipital regions and gamma band between centro-parietal and parieto-occipital regions. Also, the study reported inter-brain synchronization in the right parietal regions having importance in self-other discrimination.

Apart from the studies, Yun et al. [77] investigated the behavioural and neural correlates of interpersonal interaction in a leader-follower task. The study showed that a social interaction task such as following the finger movement of another person changed the functional connectivity of the brain. Lindenberger et al. [70] found intra-brain and inter-brain synchronization in theta band when the guitarists started to play a melody together. Another study [99] examining neural correlates in ensemble music performance found a power decrease in the alpha band while the musicians observing their own performance. The studies, also, stated that the temporal and parietal regions might be associated with music production and interpersonal action coordination. In addition to musical performance, recently, card games have been popular to perform EEG hyperscanning paradigms in more natural way, and to identify neural correlates of subjects within a team. In the study conducted by Babiloni et al. [88], EEG hyperscanning was performed while 4 subjects were playing a cooperative card game, in which two subjects against other two. They showed the activation of anterior cingulated cortex (ACC) in the leader's brain (i.e. the first player putting the first card in the specified round). While waiting to play the card in response to the other player, a correlated activity was found in the right prefrontal and parietal regions of the second player. In line with this study, Astolfi et al. [90] showed functional connectivity between two prefrontal region of the leader (the first player), and between the parietal and anterior cingulate cortex of the second player. Game theory, also, has been utilized to investigate the neural correlates of cooperative and non-cooperative behaviours. Utilizing Prisoner's Dilemma, the most popular cooperation game, Fallani et al. [19] showed the importance of the frontal and pre-frontal regions to discriminate collaborative and selfish behaviours.

2.4.1 Regions of Interest

When a person interacts with others or performs a cooperative task with others, specific brain areas activate, Thus, segmentation of EEG Networks into Regions of Interest (ROIs) is crucial to get more meaningful and accurate results.

The human brain consist of three main divisions; cerebellum, brain stem and cerebrum including the cerebral cortex. As shown in Fig.2.2, the cortex consists of four main lobes: the frontal lobe including Broca's area, parietal lobe including Wernicke's area, occipital lobe and temporal lobe [100].

In adults, the mentalizing system (MS) and the mirror neuron system (MNS) contribute to social interaction. The MS involving the medial prefrontal cortex (mPFC) and the temporal-parietal junction (TPJ) is important to anticipate intention of other people during social interaction. For instance, the mPFC was active in case a person thought about interacting partner's intentions [18,53,87]. It has been shown that the activation of the anterior cingulate cortex (ACC) and surrounding mPFC is associated with feedback processing, attention and performance monitoring [13, 101]. In addition, it has been observed that focused attention led to stronger ACC activity [102]. The oscillatory characteristics of the mPFC has been found in the frontal midline region (channel Fz) [103]. On the other hand, the MNS including the left inferior frontal gyrus (IFG), inferior parietal lobule (IPL) and premotor lobes is associated with imitation of others' actions and preparation of one's own actions [68]. Prefrontal region appeared active during the early stages of learning, and supplementary motor area (SMA) and primary motor cortex (located in the frontal lobe) appeared while learning motor skills [26]. The IPL and IFG were found more active in a joint condition than the solo one [3]. Fronto-parietal (Fp) coupling has been found associated with inter-personal awareness [104] and interactive action-perception loop [53], Also, the coupling of the comprehension-based (e.g., TPJ and Wernicke's area) and production-based areas (e.g., Broca's area) have been found within communication [80]. The left and right hand motor imagery were observed over the central lobe (C3, Cz and C4) [105].

In line with these studies, Babiloni et al. [88–90] has found the maximum activation of the ACC in the first player's brain because the ACC is associated with the generation of an accurate prediction about the behaviour of other players. Additionally, previous studies on hyperscanning [1,20,68] stated that the right centro-parietal region (channel C4, CP2, P4 and CP6) played a key role in synchronization of movements and non-verbal social coordination. Also, the centro-parietal region was active during top-down movements [20]. Inter-brain connections have been found in the ACC (central region), parahippocampal gyrus (PHG; central region), inferior frontal gyrus (IFG; frontal region) and postcentral gyrus (PoCG; parietal region) as a signature of implicit interpersonal interaction [77]. In musical performance, inter-brain phase synchronization was found between the frontal and central regions [69]. Fronto-central region is associated with representation of one's own and the other person's actions in real time [69]. The subjects' role differences such as leader-follower [89] or model-imitator [20] were observed in the frontal lobe.

2.4.2 Neuromarker

Neuromarker is a measurable signature of biological processes, used in the field of Neuroscience [55, 106]. Neuromarkers are important to describe functional neural

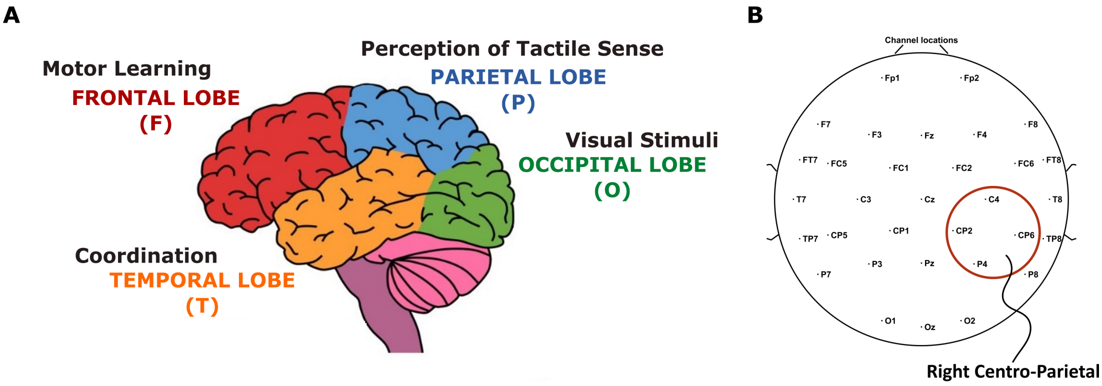

Figure 2.2: Regions of Interest (A) Cerebral cortex including four lobes: frontal, temporal, parietal and occipital. Adapted from [83] (B) Right centro-parietal region including CP2, C4, CP6 and P4.

networks during social interaction.

Brain waves are mainly divided into five specific ranges: delta (1-4 Hz), theta (4-7 Hz), alpha (8-13 Hz), beta (13-30 Hz), and gamma (>30 Hz) bands [83]. The alpha, beta and gamma waves were employed to compare synchronized and non synchronized movements [20]. The interbrain dynamical networks of phase synchronization were found among alpha-mu, beta and gamma frequency bands. In addition to them, Tognoli et al. [1] defined three frequency range within the 7.5-13 Hz: Mu (7.5 – 12.5 Hz), phi-1 (10-12 Hz) and phi-2 (12-12.5 Hz) associated with social interaction.

Mu, alpha and phi complex including phi-1 and phi-2 appeared in synchronic social behaviours such as executing joint tasks [1, 55]. Alpha waves were found more visible over the occipital or parietal lobes whereas beta waves were found especially in the frontal or central lobe [53, 83]. The mu rhythm was found above Rolandic region as a further index of motor activity [1, 53]. EEG components related to movement appeared mostly in the alpha band [27]. The power of alpha-mu rhythm (8-12 Hz) decreased in the sensory motor area while planning and executing hand movements [53, 107], whereas the power of beta rhythm decreased with arm movements [108–110], Considering motor tasks, practice and successful trials resulted in higher theta synchronization in the frontal region [108]. Alpha rhythm mostly found in parietal and occipital lobes is a key signature of visuo-motor tasks [55] such that the alpha power increased at occipital lobe with eye open [111]. When comparing experts and novices, novices exhibited higher synchronization in the alpha, high beta and gamma frequency band [112]. Also, the activation of the anterior cingulate cortex (ACC) and the medial prefrontal cortex (mPFC) has been shown in the theta band (4 –8 Hz) [101, 103, 108]. Previous hyperscanning-EEG studies showed that inter-brain phase synchronization occurred in theta and beta frequency band due to the practice in a motor task [77]. Increase in attention led to power decrease in the alpha band [113].

2.5 Conclusion

While learning skills through the interaction with others, humans can face a dual instability arising from the environment and the interaction with a partner (Fig.2.3).

Previous research focused on skill learning mostly through adaptation to environmental dynamics [10, 11, 32]. However, the adaptability to others has not been investigated, because motor skill learning was evaluated by comparing individual and dyadic performance. It still remains unclear what kind of motor experience facilitates the adaptability to others. Thus, our first study (Chapter 3) aims to investigate the adaptability of novice subjects to unfamiliar partner after they experienced cooperative motor learning with a different skill level partner (novice or expert agent). We, also, suggest that in the previous literature [2, 11], the confusion originates from the fact that skill transfer and mutual interactions were studied independently. Thus, our second study (Chapter 4) aims to investigate the relationship between skill learning and adaptability to others, and seek for the conditions which can induce the best motor learning. In the third study, we defined a new paradigm where the joint cursor is a true representation of the dual instability (environment and partner's dynamics). This study aims to investigate how the order of unknown dynamics (e.g., environmental or/and partner dynamics) affect skill learning process. Note that, the participants negotiate their intentions with their partners via haptic interaction. Lastly, we implemented an EEG-hyperscanning study to find the neuromarkers of dyadic haptic interaction and mutual skill learning (Chapter 6).

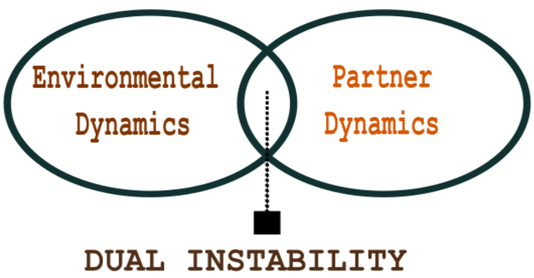

Figure 2.3: The issue of dual instability due to partner or/and environmental dynamics in a human-human interaction.

Chapter 3

Cooperative Visuomotor Learning Experience with Peer enhances Adaptability to Others

While learning skills through the interaction with others, humans can face a dual instability arising from the environment and the interaction with a partner. The research to date focused on skill learning mostly through adaptation to environmental dynamics by comparing individual practice and learning with a partner (novice or expert). However, there is an open question what kind of motor experience facilitates the adaptability (adaptation to others). This chapter investigates adaptability in a cooperative motor task by comparing novice-to-novice and novice-to-expert interaction. It is important to note that there is no applied task-related haptic feedback while the subjects are interacting with each other. The results suggest that practicing with another novice is more advantageous than practicing with an expert agent algorithm to demonstrate adaptability to others. We suggest that the results might be informative for training in team sports. Having the novice-to-novice sessions in the team sports would promote the adaptability to other players and reform their actions. The results, also, would be useful for motor learning through human–robot interaction such as robot-assisted human motor learning.

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FULL PAPER

Cooperative visuomotor learning experience with peer enhances adaptability to others

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ABSTRACT
Skilled musicians can improvise with first-time partners. Thus, the question arises how the adaptability to others can emerge through the mutual motor learning experience. We developed a two-person cooperative visuomotor task; an object was connected through virtual springs with the cursors controlled by the subjects. We instructed paired subjects to jointly control the object toward a specified target under a virtual force field. Experimental results suggest that a novice subject who was trained with a skill-level matched peer in the Learning phase showed significantly better adaptability to others in the successive Evaluation phase. Variety of the cooperative experience with others in the visuomotor task probably gave rise to high adaptability in the novice-to-novice group subjects, while the learning experience with an expert did not. We conclude that the motor skills acquired during mutual interactions with peers can lead to have an ability to tune the motor commands subject to the dynamics of the external environment and the behavior of the partners.

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1. Introduction

For social animals, moving bodies together in harmony plays an important role in facilitating social interactions. In humans, such coordinated actions are common from mutual interactions to group activities such as playing music and dancing [1–4]. To coordinate one's own motion in harmony with a partner's motion, anticipating the partner's motion at the next moment is crucial to overcome a substantial time delay between the perception and the actuation of the coordinated body motion [5–7].

Since birth, we learn ways to control our body, using motor skills and embodying tools as if there were a part of our body. Motor learning is defined as a set of internal processes within the brain, leading to relatively permanent changes in the capability for new motor skills. Motor learning has been studied mostly through adaptation in motor tasks by introducing perturbation such as visuomotor transformations or virtual force fields in reaching tasks [8–11].

In the human motor learning context, transfer of a motor skill from an expert to a naïve person plays an important role, for example, in teaching how to dance, much of knowledge transfer is done implicitly through visual and haptic interactions rather than verbally. With the focus on the ability of physically coupled subjects to adapt to cooperative visuomotor task, Mireles et al. [12] investigated how training in pairs for a cooperative task (arm reaching task with left or right hand) and their skill-level matching (novice-to-novice or novice-to-expert) affect the development of individual motor skills (bimanual reaching task) for unknown environments, and reported that the skill transfer from expert to novice is possible only when the novices have a chance to perform the task first on their own. It suggests that solving the dual instability problem, i.e. discriminating the unknown environmental dynamics [13] and the dynamics of partner is important. Moreover, they suggest that cooperative motor learning with a novice rather than an expert is promising for improving the individual motor performance. Ganesh et al. [14] demonstrated that an implicit haptic intervention from the other subject who engaged in the same task simultaneously has a positive effect on the further individual motor performance regardless of the partner's skill level.

According to the background, the adaptation ability (hereafter *adaptability*) to others can be considered as a key skill for improvising with others. In most motor

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learning literature, however, the adaptability to others has not been investigated, because the validation of the motor skill was evaluated with the learning partner or individual [12, 14], thus it is an open question what kind of motor experience facilitates the adaptability. To study the problem, we executed a motor learning experiment [15], where a participant executed a cooperative visuomotor task with a human partner with different skill levels (novice or expert), and found that the motor experience with a novice partner (a peer of the participants) is superior to the experience with an human expert (an experimenter who well understood the task) even in the cooperation with a first-time partner. Our previous result suggested that variety of motor execution in cooperation with novices is a significant factor for facilitating the adaptability to others, however, there still remains the problems: the validity of the human expert, i.e. whether the experimenter (human expert) has been a true expert of the task, and whether the expert had always been able to interact with the participant in the same way, because human operation would have variability in motor coordination. Due to this, we hypothesized that variety of motor execution in cooperative motor learning promotes the adaptability to others. The aim of the present study is to develop an artificial agent model which represents the guidance of a human expert and to clarify the validity of the hypothesis.

In this study, we developed a cooperative visuomotor task only using visual feedback based on the referenced paper by Mireles et al. [12], and investigate the adaptability of novice subjects to unfamiliar partner after they experienced cooperative motor learning with a different skill level partner.

2. Materials and methods

2.1. Subjects

Thirty-two human subjects (25 male and 7 female, average age 21.97 $\pm$ 4.03 years) participated in the experiment and provided written informed consent. Two male and one female were left-handed and the rest were right-handed according to the Edinburgh Handedness Inventory [16]. All subjects used their dominant hand in this study. This experiment was approved by the ethical committee of the Tokyo University of Agriculture and Technology (No. 28-33).

2.2. Experimental paradigm

We developed a cooperative visuomotor task shown in Figure 1(A), in which each of the paired subjects was asked to operate the left cursor (yellow filled circle) or right cursor (red circle) individually in order to bring a joint cursor (blue circle, hereafter dubbed as virtual object) to a target (white circle). The virtual object was connected to both cursors with virtual elastic springs. This figure indicates the initial configuration of the task. As shown in the figure, each cursor was controlled by each subject via analogue joystick (TUFB-A01-1, Technotools Co., Japan). The roll and pitch angles of the joystick were linearly corresponded with the Cartesian coordinates of the cursor position on the display, allowing the cursor to travel within a circular region, and to return to the central start position when the joystick was released. Note that these joysticks have no mechanism for force feedback, thus there is no task-related haptic feedback while the subjects are interacting with each other through the virtual springs. The platform of the cooperative task was developed using MATLAB software (The MathWorks Inc., MA, USA).

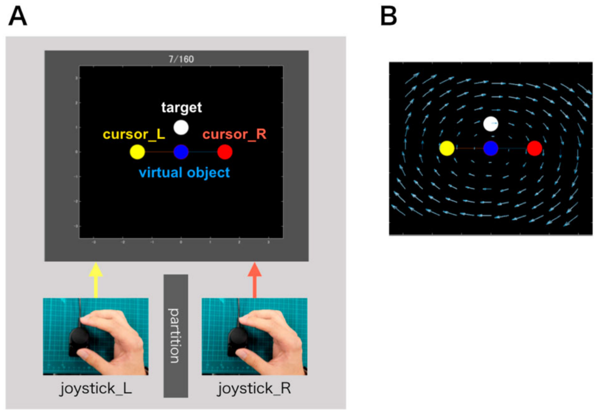

Figure 1. (A) Appearance of a cooperative visuomotor task. Virtual object (blue filled circle) was connected to both left and right cursors (yellow and red filled circles) with virtual elastic springs. The subjects were instructed to jointly move the virtual object toward randomly emerging target (white filled circle) by operating their analogue joystick. (B) Virtual force field assumed in the training condition. The virtual object receives an unfamiliar external force from the environment. The virtual force can be visually perceived as the motion of the virtual object.

In the experiment, the target was randomly appeared at one of eight candidate locations which were equally spaced at 45° on a circumference around the start position, and also the initial task configuration was rotated accordingly. The subjects were instructed to move the virtual object to the target as fast as possible when the target appeared.

Additionally, to make it a motor learning task, we assumed a position-dependent force field in the environment (Figure 1(B)), and that the unfamiliar external force affects the motion of the virtual object. The equation of the force field is as follows:

$$\vec{F}_e = \begin{bmatrix} 0 & K_e \\ -K_e & 0 \end{bmatrix} \vec{P}, \quad (1)$$

where $\vec{P} = [x, y]^T$ corresponds to the position vector of the virtual object in the Cartesian coordinates, $\vec{F}_e = [f_x, f_y]^T$ is the external force vector applied to the virtual object, and K_e is a stiffness constant. It was designed to generate a clockwise rotated elastic force field. As there was no task-related haptic feedback, the subjects had to perceive and compensate for the disturbing force based on the visual feedback through the relative motions between the virtual object and two cursors on the display.

The dynamics of the virtual object can be described using the following equations of motion:

$$M \frac{\mathrm{d}^2}{\mathrm{d}t^2} \vec{P} + B \frac{\mathrm{d}}{\mathrm{d}t} \vec{P} = \vec{F}_{\mathrm{L}} + \vec{F}_{\mathrm{R}} + \lambda \vec{F}_e, \quad (2)$$

where M and B are the inertia and viscosity constants. $\vec{F}_L$ and $\vec{F}_R$ correspond to the acting forces from the cursors calculated as,

$$\vec{F}_{\mathrm{L}} = -K_s \left(\vec{P} - \vec{P}_{\mathrm{L}} \right), \quad (3)$$

$$\vec{F}_{\mathrm{R}} = -K_s \left(\vec{P} - \vec{P}_{\mathrm{R}} \right), \quad (4)$$

where $\vec{P}_{\mathrm{L}}$ and $\vec{P}_{\mathrm{R}}$ are the position vectors of the left and right cursors, and K_s is the stiffness parameter of the virtual springs. These task parameters were experimentally determined ($M = 1, B = 100, K_s = 1000,$ and $K_e = 2500$) such that the task cannot be completed through the operation of a single-side cursor alone. Moreover, λ is a session mode selector ($\lambda = 0$ in the Familiarization session, while $\lambda = 1$ in the Training session, explained later).

2.3. Experimental groups and protocols

To investigate the effect of the skill level of the learning partner on the subsequent performance of cooperative motor task, we designed an experimental protocol, and set up two groups as shown in Table 1.

All subjects were novice and randomly assigned to one of two experimental groups: NN (Novice and Novice) or NE (Novice and Expert). Throughout the experiment, half of the subjects in each group played the role of the right cursor operator, while the rest were the left cursor operator.

The experiment consisted of three phases: Baseline, Learning, and Evaluation phases, and each phase included two types of sessions: Familiarization session (hereinafter referred to as FS) in which the subjects were familiarized with the experimental protocol without the effect of unknown external force field, and Training session (TS), where the subjects were trained in the environment with the force field. In the Baseline phase, each pair executed 6 sets of FS, and 1 set of TS. The performance measured in the TS of this phase can be considered as the baseline performance of the pair. In the following Learning phase, 3 sets of FS and 20 sets of TS were assigned. During the TS in the Learning phase, subjects in the NN group had to learn the cooperative visuomotor task with another novice in the same group, while the subjects in the NE group executed the task with a programmed expert agent. To investigate the adaptability of the subjects, they performed 3 sets of FS and 6 sets of TS in the Evaluation phase.

Note that the paired partners were swapped within the same experimental group during the Learning phase, to evaluate individual adaptability in the Evaluation phase appropriately. For example, subject A executed the cooperative task with subject D, instead of subject B in the Learning phase (see Table 1).

Table 1. Experimental phases and groups.

Groups	Baseline phase (6-FS, 1-TS)	Learning phase (3-FS, 20-TS)	Evaluation phase (3-FS, 6-TS)
NN	$S_A - S_B$	$S_A - S_D$	$S_A - S_B$
($n = 16$)	$S_C - S_D$	$S_C - S_B$	$S_C - S_D$
	⋮	⋮	⋮
NE	$S_I - S_J$	$S_I - A, A - S_J$	$S_I - S_J$
($n = 16$)	$S_K - S_L$	$S_K - A, A - S_L$	$S_K - S_L$
	⋮	⋮	⋮

Notes: In both Baseline and Evaluation phase, all the subjects were asked to execute a cooperative visuomotor task with their pre-assigned human partner, while in the Learning phase they had to perform the task with another novice subject in the same group (NN group) or with a programmed expert agent denoted as A (NE group). In this manner of having training sessions with another partner, we could investigate 'the adaptability to others' and motor learning process of adapting to a new person with respect to the baseline performance measured in the Baseline phase. For example, subject A (S_A) executed the task with subject B (S_B) in the Baseline and Evaluation phases, but he/she performed the task with another subject, subject D (S_D) in the Learning phase.

2.4. Expert agent

In the Learning phase, the subjects in the NE group trained the cooperative visuomotor task with a programmed expert agent. The agent was designed to behave optimally like a human expert in [15], who well understood the dynamics of virtual force field. The following algorithm was implemented.

The algorithm consists of two parts, update of the desired position for the agent's cursor and proportional control to update the current position. First, the desired position along the x-axis for the agent cursor, $\hat{A}_x$ is given by $(\hat{A}_x + P_x)/2 = T_x - \alpha F_x$ where P_x is a x component of the partner's cursor, T_x is a x component of the target position in the reaching task, and αF_x is a x component of the displacement caused by the force field at the current position of the virtual object, i.e. α is a parameter for dimensional adjustment, which was set to 1.0 in the experiment. The identical algorithm was applied for the y component of the agent cursor. Thus, the desired position for the agent cursor was determined to jointly move the virtual object to the target, compensating the current force field.

Second, the proportional control was applied to minimize the relative distance between the desired and current positions of the agent cursor, $A_x = A_x + \beta(\hat{A}_x - A_x)$, with the gain parameter $\beta = 0.125$. Note that when updating the desired position of the agent cursor, the time delay of 400 ms was introduced to simulate the visuomotor delay of humans, which was experimentally determined based on the results of our previous study [15]. Therefore, the update of the current position was based on the kinematic data of the partner's motion at 400 ms in the past. Moreover, a small Gaussian noise was added to the desired position of the expert agent, thus, avoiding the possibility of the agent cursor's movement being perceived as mechanical.

2.5. Performance index

As the criterion for evaluating the performance of cooperative motor task, we defined the combined index (CI), which is the product of the total time required to achieve the task (time-to-target index) and the total traveling distance of the virtual object (distance index). Analysis of the result from a pilot study indicated that the CI immediately decreases across the trials, revealing that it forms a log-normal distribution. Thus we decided to use the logarithm of CI (i.e. log CI) in the statistical analysis.

3. Results

Figure 2 demonstrates the transitions of combined index (log CI) averaged within each group, measured in TS of the Baseline, Learning, and Evaluation phases. Note that each pair in both Baseline and Evaluation phases is identical, but the pairs during the Learning phase were swapped within the same group (see Table 1).

As shown in the Baseline phase of the figure, both groups showed almost same performance in average, however we can see that the pairs in the NN group indicated better averaged performance compared with the NE group in the Evaluation phase. On the other hand, we can confirm that the pairs in the NE group demonstrated superior performance in the Learning phase.

In order to investigate the effect of skill-level matching during cooperative visuomotor learning in the Learning

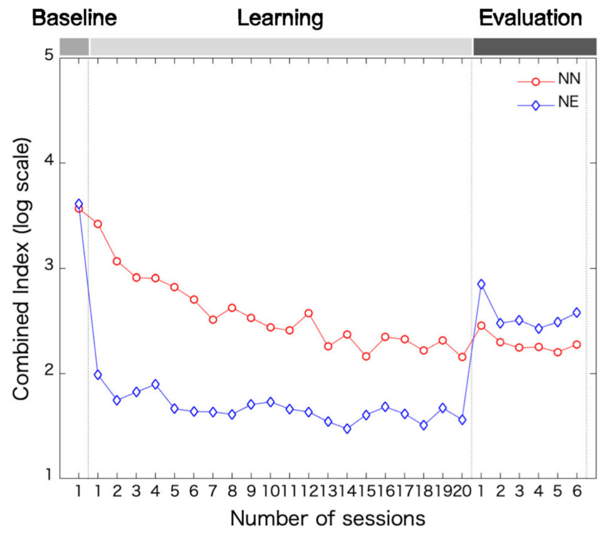

Figure 2. Transitions of combined index (log CI) measured in the Training Session of the Baseline, Learning, and Evaluation phases. Each marker represents the median within the group.

phase, we statistically evaluated the performance of the cooperative visuomotor task at two distinct ROI (region of interest) time-points: i.e. TS in the Baseline phase and the first TS in the Evaluation phase. A 2×2 repeated-measures ANOVA (groups $\times$ phases) was applied to the log CI, and significant interaction effect ($F(1, 14) = 8.89$, $p < .01$) was confirmed. Thus, we firstly tested simple main effect on phases in each group using paired t-test, and confirmed significant differences in both groups ($p < .01$ for both). In addition, we performed further analysis on the difference of experimental groups regarding each phase using Weltch's t-test.

As shown in Figure 3, no significant difference between the groups was confirmed in the Baseline phase ($p = .355$). This indicates that the task performance of the individual pairs in both NN and NE groups was more or less at the same level in the first encounter. In the first TS of the Evaluation phase, on the other hand, each subject was paired with the partner in the Baseline phase, who can be considered as a different partner of cooperative visuomotor learning, we found a significant difference between the NN and NE groups ($p < .01$). This result indicates that the subjects in the NN group showed superior performance with a novel partner in the cooperative task rather than the those in the NE group.

Moreover, to be clear the effect of training group on the Evaluation phase, we executed additional 2×6 repeated-measures ANOVA (groups $\times$ trials) with respect to the performance indexes in the phase. It revealed no interaction effect ($F(5, 70) = 1.067$, $p = .386$), but main effects for groups ($F(1, 14) = 7.384$, $p = .0167$) and trials ($F(5, 70) = 5.873$, $p = .000138$). This implies that the

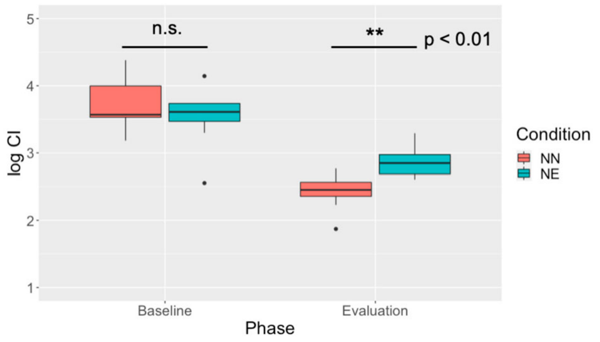

Figure 3. Statistical comparison of log *CI* between the Training Session of the Baseline phase and the first Training Session of the Evaluation phase.

experience in the Learning phase has different effect among the groups, i.e. cooperative motor learning experience with novice peer is superior to the experience with the expert agent, in the future adaptability. Thus, we could verify our hypothesis that training with the novice subject helped to demonstrate adaptability to others, whereas pairing with the expert agent did not have the skill transfer effect.

4. Discussion

In the case of physical human–human interaction, the sensory feedback exchanged among one another can become a channel for the mutual sharing of intentions, and plays a primary role in the construction of a shared motor plan in order to achieve a task together. A recent study showed that the skill transfer from the expert to novice subject through visual and haptic interactions is possible [12].

However, the focus has been only on the improved performance of the individual, i.e. the nature of the mutual interactions between the expert and novice, e.g. adaptability to others, has not been explored.

When cooperating with others, predicting the motion of the partner at the next step is critical as feedback control adjusting motion is subject to the time delay [17]. Here, for such prediction, an internal model of the partner is necessary to simulate the motion of the partner in response to which one can perform an action.

Through iterative active-perception of how the other partner moves in response to one's own motion, we consider that one can develop the plastic internal model, which can be used to predict the next motion of the partner. If one can build up the plastic internal model that can simulate the dynamics of others, one can adapt to a new partner and cooperate with him/her quickly to achieve a cooperative task. On the other hand, interacting with the expert would prevent the development of the plastic internal model of the partner as the interaction with the expert tends to be one directional, given the lack of real-time action-perception loops, though the subjects could learn the integrated dynamics of the expert agent and environment.

Now, let us take a close look at the internal model developed in the Learning phase. As shown in Figure 2, the novice participants in the NE group showed a better motor performance than those in the NN group in the Learning phase. Thus, the programmed expert agent could play a certain role in guiding the participants through the unknown environmental dynamics.

From the motor performance of the novice participants in the Learning phase, we can assume that they could acquire the integrated internal model to cope with the dual instability, i.e. the partner dynamics and environmental dynamics. However, if the partner is the expert agent, the integrated internal model cannot produce appropriate motor commands to immediately cooperate with another new partner, thus, 'adaptability' to a new partner should be realized by immediate tuning of the motor commands would play a critical role for immediate cooperation, and it is needless to say that the real-time adaptation should be based on the real-time feedback loops and sensory input.

On contrary, as shown in Figure 3, we found that the novice participants who were trained with another novice in the Learning phase could gain this adaptability for the immediate tuning. This is because the participants in the NN group can experience a wide range of motor coordination together while exploring the unknown external force field, leading to higher adaptability to a new partner in the Evaluation phase.

Note here that in this study, motor learning paradigm is limited to the visual feedback for investigating the sensory feedback effect independently, in order to clarify if somatosensory feedback is absolutely necessary for learning the cooperative task in the similar paradigm.

As a result, we could show that participants can learn the cooperative task only through the visual feedback loops.

This study has some potential limitations. The results reported here might be linked to the specificity of the cooperative motor task used in this study. And the adaptability we considered here is limited to the other partners, not to other tasks. Most significant limitation is that we adopted a human partner in the Learning phase of the NN group as opposed to the expert agent in the NE group. Although we consider that the adaptability to others is endowed by the variety of interaction, we cannot discard the possibility that it depends on human intervention. In addition, there is another possibility regarding the skill level of the partner, i.e. mutual learning on the peer-to-peer basis, rather than just facing a variety of motor coordination patterns. This point will be persuaded in the future study by developing the novice agent.

Our results are informative for training in team sports. We suggest that having the novice-to-novice sessions in the team sports would promote the adaptability to other players and reform their actions [18]. This finding would be useful for motor learning not only through human–human interaction [19], but also human–robot interaction such as robot-assisted human motor learning [11, 20] and physical therapy [21].

5. Conclusion

In this study, we investigated the hypothesis that the cooperative motor experience with novices is superior to the experience with an expert agent algorithm in terms of promoting adaptability to others. The experimental result suggests that poor adaptability of the participants who were trained with an expert agent is not due to a particular human experimenter and less variability, but a fixed strategy designed to behave optimally.

Disclosure statement

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Chapter 4

Mutual Skill Learning and Adaptability to Others via Haptic Interaction

Skill learning is the result of the interactions between the learner and the learning environment. Performance improvement depends on adaptation to the environmental dynamics in the individual practice, whereas in the dyadic interaction, it depends on not only adaptation to the environmental dynamics but also partner dynamics.

This chapter aims to investigate the conditions which can induce the best motor learning. When learning a new skill under an unknown environment, should we practice alone, or together with another beginner, or learn from the expert? The results are consistent with the results presented in chapter 3 even though there is an additional task-related force in addition to visual feedback. Having the novice-to-novice interaction is more advantageous for adaptability and motor learning than practicing under the expert's guidance. We suggest that novice-to-novice learning would work, as they have more chances to explore the unknown external field, resulting in increasing the adaptability to others. The results are very informative for training sessions in the activities requiring cooperation and coordination such as dance or ensemble music performance. Also, the results will be useful to further investigate motor learning during human-human interaction and, also, to develop the human-machine interfaces which can be implemented in robots making a contact with humans for elderly care or rehabilitation.

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Mutual Skill Learning and Adaptability to Others via Haptic Interaction

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When learning a new skill through an unknown environment, should we practice alone, or together with another beginner, or learn from the expert? It is normally helpful to have an expert guiding through unknown environmental dynamics. The guidance from the expert is fundamentally based on mutual interactions. From the perspective of the beginner, one needs to face dual unknown dynamics of the environment and motor coordination of the expert. In a cooperative visuo-haptic motor task, we asked novice participants to bring a virtual mass onto the specified target location under an unknown external force field. The task was completed by an individual or with an expert or another novice. In addition to evaluation of the motor performance, we evaluated the adaptability of the novice participants to a new partner while attempting to achieve a common goal together. The experiment was set in five phases; baseline for skill transfer and adaptability, learning and evaluation for adaptability and skill transfer respectively. The performance of the participants was characterized by using the time to target, effort index, and length of the trajectory. Experimental results suggested that (1) peer-to-peer interactions among paired beginners enhanced the motor learning most, (2) individuals practicing on their own (learning as a single) showed better motor learning than practicing under the expert's guidance, and (3) regarding the adaptability, peer-to-peer interactions induced higher adaptability to a new partner than the novice-to-expert interactions while attempting to achieve a common goal together. Thus, we conclude that the peer-to-peer interactions under a collaborative task can realize the best motor learning of the motor skills through the new environmental dynamics, and adaptability to others in order to achieve a goal together. We suggest that the peer-to-peer learning can induce both adaptability to others and learning of motor skills through the unknown environmental dynamics under mutual interactions. On the other hand, during the peer-to-peer interactions, the novice can learn how to coordinate motion with his/her partner (even though one is a new partner), and thus, is able to learn the motor skills through new environmental dynamics.

Keywords: physical human-robot interaction, human-human interaction, collaborative learning, motor learning, skill learning, adaptability

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1. INTRODUCTION

As social beings, humans need to learn a variety of motor skills to perform everyday tasks. Skilled motor behavior is necessary for many human activities, such as daily life activities (e.g., driving), sport activities (e.g., basketball), art performances (e.g., playing musical instruments), and occupations (e.g., surgery). Auditory (Konvalinka et al., 2010; Wolf et al., 2018), visual (Newman-Norlund et al., 2008) or haptic feedback (van der Wel et al., 2011; Madan et al., 2014; Takagi et al., 2017; Özen et al., 2020) is important to coordinate actions and learn new skill sets in a cooperative task, such as ensemble music performance or dancing.

From birth, humans learn how to use motor skills and control their movements. In motor learning tasks, transferring a skill from an expert (a teacher or a coach) to a novice (a learner or a player) plays an important role. Learning and teaching (Bremmer and Nijs, 2020), which are mutually complementary terms associated with an interactive experience between the expert and the novice, appear in physical activities, such as dance as well as in rehabilitation. For example, in teaching dance, an expert may teach a novice how to dance by using the haptic interaction associated with moving in synchrony or by guiding desired movements. Physical therapists guide their patients *via* haptic interaction to help the person learn or relearn specific movements (Sawers and Ting, 2014). In rehabilitation, in addition to physical therapy provided by therapists, the recent technological advancements paved the way for the usage of robotic systems in helping humans to improve their motor skills and motor recovery and robot-assisted therapy in stroke rehabilitation (Wei et al., 2005).

More generally, in recent years, there has been a growing interest to create robots having the ability to interact with humans in a more natural manner (Nasr et al., 2020). It is important to create robotic systems which can provide more natural human-robot interactions. Thus, first, understanding the nature of human-human interaction is an important step, i.e., understanding in such a way that how a coach, athletic trainer, teacher, or physical/occupational therapist facilitate the learning process (Ganesh et al., 2014; Sawers and Ting, 2014; Mireles et al., 2017; Takagi et al., 2017). The previous studies (Ganesh et al., 2014; Beckers et al., 2018) found that a paired performance is more advantageous than an individual performance in motor learning, which has been proved by connecting two participants to each other *via* virtual spring while tracking the virtual target by controlling a haptic interface.

Here, a haptic interface (Hernantes et al., 2012) is a device that includes a robotic mechanism along with sensors to determine position of humans in the virtual environment and actuators to apply forces to the operator and is used to manipulate an object within a virtual environment. The usage of robotic haptic interfaces generating force-field paved the way for understanding the human mechanism while learning skills through dyadic haptic interaction. In the case of dyadic interaction, humans can face a dual instability arising both from the environment and the interaction with a partner (De Santis et al., 2014; Mireles et al., 2017). As shown in the cases above, it is normally helpful for novice participants to learn the motor skills through the unknown environmental dynamics with an expert guiding through unknown environmental dynamics. However, as the guidance from the expert is fundamentally based on mutual interactions, from the perspective of the beginner, one needs to simultaneously face dual unknown dynamics of the environment and motor coordination of the expert. When the beginner learns a task with a partner, one needs to learn how to coordinate the body motion, predicting the next motion of the partner. This inevitably involves the process of adaptation to the partner. Here, as opposed to the normal assumption where the guidance from the expert is always helpful, we hypothesize that learning with another beginner would enhance motor learning as a result of peer-to-peer learning, adapting to the other's dynamics, and exploring the unknown environmental dynamics together. Thus, the fundamental question is, when learning a new motor skill, whether we should practice alone, or learn from the expert, or learn together with another beginner. To date, several studies (Masumoto and Inui, 2013; Ganesh et al., 2014; Mireles et al., 2017; Kostrubiec et al., 2018) investigated skill learning by comparing paired performance and individual performance, and found that the paired one showed better motor performance than the individual one. The studies indicating the importance of dyadic interaction in skill learning lead us to consider the effect of the interacting partner on skill learning. The recent study (Mireles et al., 2017) employing novice-to-novice and novice-to-expert interactions suggested that in cooperative tasks the best performances were induced during the training with an expert, but the novices trained with an expert were not able to perform the task well when the expert is removed. That is to say, the study (Mireles et al., 2017) highlighted the importance of exploration of the environmental dynamics in the cooperative task for skill learning. The research to date (Shadmehr and Mussa-Ivaldi, 1994; Krakauer et al., 1999; Sakamoto and Kondo, 2015) focused on skill learning mostly through adaptation to virtual force fields or visuomotor transformations in reaching tasks. However, how a human learns to adapt to the dynamics of a partner during the novice-to-novice interaction remains still unclear.

Skill learning is the result of the interactions between the learner (novice) and the learning environment (Bremmer and Nijs, 2020), so in the individual performance, the improvement depends on the adaptation to the environmental dynamics, whereas in the dyadic interaction, it depends on not only adaptation to the environmental dynamics but also dynamics of partner (Magill and Anderson, 2010; Jundt et al., 2015). For example, in paired skating, to perform common trajectories on the ice ground, an ice skater is trained to adapt to the environmental factors and understand the actions of the partner.

In the previous literature, the confusion originates from the fact that skill transfer and mutual interactions were studied independently. It means that much uncertainty still remains about the nature of motor skill learning under the unknown environment where it inevitably involves mutual interactions. Thus, we aim to study the relationship between skill learning and adaptability to others, and thus, seek for the conditions which can induce the best motor learning. To this end, a

TABLE 1 | Experimental protocol.

(A) Novice-Novice (N-N) and Novice-Expert (N-E) groups

	Baseline of skill transfer B-S (1-FS, 2-TS)	Baseline of adaptability B-A (2-FS, 1-TS)	Learning (2-FS, 30-TS)	Evaluation of adaptability E-A (2-FS, 6-TS, 2-WS)	Evaluation of skill transfer E-S (4-TS)
	N_1 | N_2	N_1 - N_2	N_1 - N_4	N_1 - N_2	N_1 | N_2
(N-N)	N_3 | N_4	N_3 - N_4	N_2 - N_3	N_3 - N_4	N_3 | N_4
($n = 12$)	⋮	⋮	⋮	⋮	⋮
	N_{13} | N_{14}	N_{13} - N_{14}	N_{13} - *Exp*, *Exp* - N_{14}	N_{13} - N_{14}	N_{13} | N_{14}
(N-E)	N_{15} | N_{16}	N_{15} - N_{16}	N_{15} - *Exp*, *Exp* - N_{16}	N_{15} - N_{16}	N_{15} | N_{16}
($n = 8$)	⋮	⋮	⋮	⋮	⋮

(B) Alone group

	B-S (1-FS, 2-TS)	Learning (2-FS, 18-TS, 2-WS)	E-S (4-TS)
(Alone)	N_{21}	N_{21}	N_{21}
($n = 3$)	⋮	⋮	⋮

(A) B-S and E-S were performed alone whereas B-A, Learning and E-A were performed with a preassigned partner (another novice or an expert). (B) The novice participants always performed the task alone without dyadic interaction (FS, familiarization session; TS, training session; WS, wash-out session).

cooperative task using a backdrivable haptic device will be employed for participants to achieve a common goal under unknown environmental dynamics. The ability to adapt to the motor coordination of other participants (adaptability to others) should be a key to exploring the unknown environmental dynamics, and thus, learning the motor skill to achieve a goal under the unknown dynamics.

We hypothesized that there should be a positive correlation between skill learning and adaptability, which means that the participants in Novice-to-Novice groups can adapt to each other by exploring the unknown environmental dynamics together, and motor skill learning can happen only when there is adaptation.

In the study, we adopted the widely used paradigm (for example, see Mireles et al., 2017), first to investigate the effect of practicing alone or training with the expert or novice partner on motor performance. Second, we studied "adaptability to others," introducing Evaluation of Adaptability (see **Table 1**) as a new experimental protocol of the participant experiments. In this paradigm, we asked the participants to guide a virtual mass to bring it to a specified target under an external force field as an individual or with their preassigned partner (expert or novice). The novice participants were engaged to learn the motor skills, manipulating the haptic device under the unknown force field. Using the detected time interval, force and trajectories during the task, we evaluated the motor learning of the novice group trained with the expert or another novice as well as the degree of adaptability. Details of the experiment are given in **Figures 1**, **2** and the section 2.

2. METHODS

2.1. Participants

Twenty-three novice persons (12 male and 11 female, average age 26 ± 3.51 years) and an expert person (female, 33 years) participated in the study and provided written informed consent. Here, the novice participant has no previous knowledge about the task and the expert has been previously trained with the task under the external force field as an individual by performing 180 and 120 trials in two consecutive days. It is known that long practice with a task can result in expertise with the task (Magill and Anderson, 2010). In our study, the results demonstrated that performing 300 trials in total was enough to provide an appropriate level of expertise to a novice person. Two male and three female novice participants were left-handed, and the rest were right-handed according to the Edinburgh Handedness Inventory (Oldfield, 1971). All participants used their dominant hand in the study. The experiment was approved by the ethical committee of the University of Reading (No.SBS18-19 28). The experimental methods were performed in accordance with the relevant guidelines and regulations.

2.2. Experimental Groups

At the beginning of the experiment, all novice participants were randomly assigned to one of three experimental groups: Novice-Novice (*N-N*), Novice-Expert (*N-E*), and *Alone* (see **Table 1**). The *N-N* group consists of 12 novices. The participants in the *N-N* group were paired with another novice participant in the Learning phase. The *N-E* group consists of eight novices and they were paired with the expert in the Learning phase. The

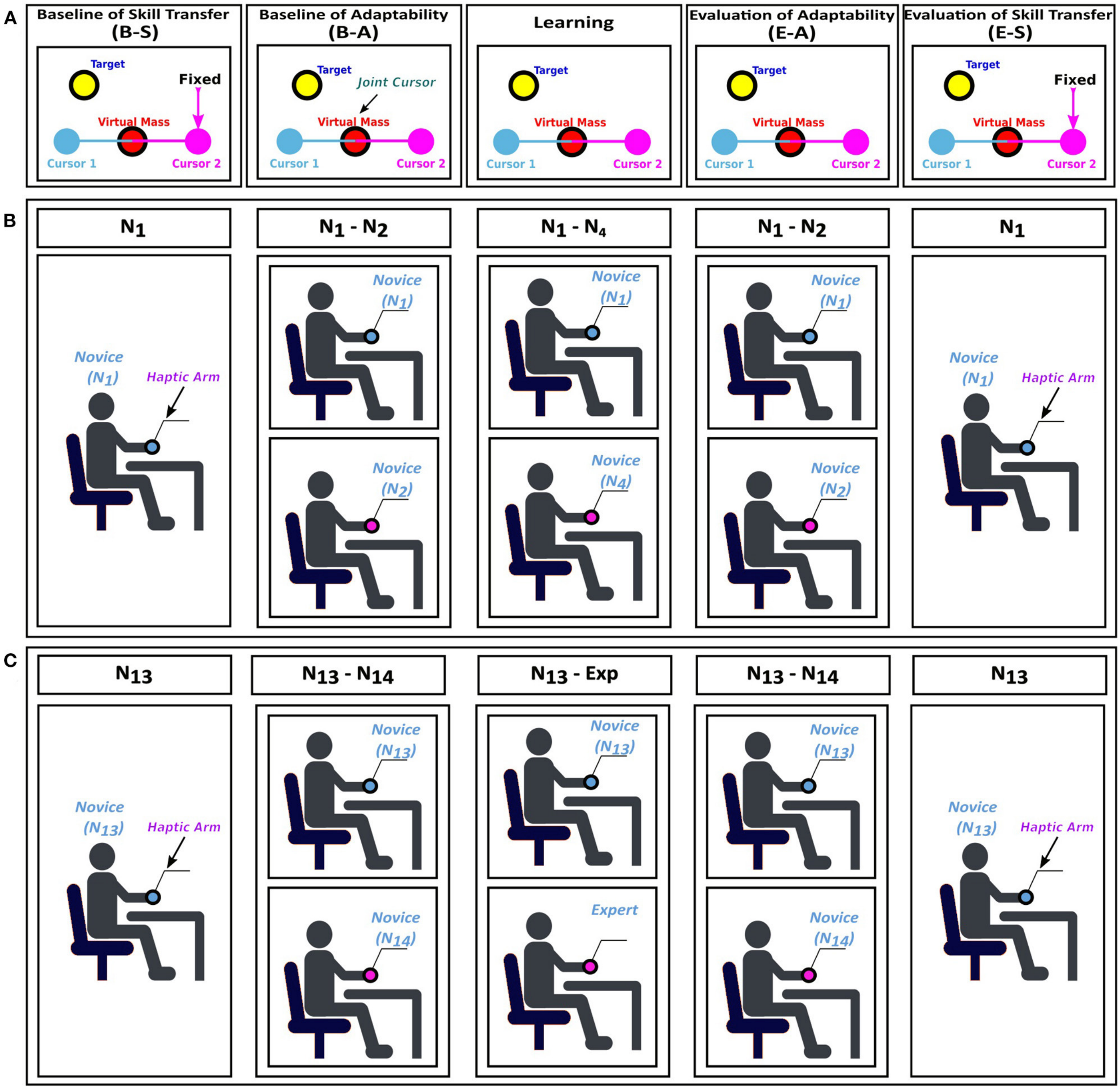

FIGURE 1 | Experimental protocol. **(A)** The structure of the virtual tool and the experimental phases for the Novice-Novice (*N-N*) and Novice-Expert (*N-E*) groups: Baseline of Skill Transfer (B-S), Baseline of Adaptability (B-A), Learning, Evaluation of Adaptability (E-A), and Evaluation of Skill Transfer (E-S). **(B)** *N-N* group; the Learning phase was performed with a new novice participant (here, *N1* and *N4*). **(C)** *N-E* group; the Learning phase was performed with an expert (here, *N13* and *Exp*).

paired participants did not meet each other prior to or during the experimental sessions. In addition, 3 novices in the *Alone* group performed all trials as an individual. The primary study was the N-N vs. N-E, and the Alone group acts as a check-mark to ensure that no factors are inadvertently overlooked.

2.3. Experimental Setup and Task

To investigate "motor skill learning" and "adaptability to others," in the light of the previous study (Mireles et al., 2017), we designed a cooperative visuo-haptic task as shown in **Figure 1**: a virtual mass (red circle) was connected to two cursors (blue and purple circles) by virtual springs (blue and purple lines). Visuo-haptic refers to the integration of visual information (e.g., the motion of two cursors on a screen) and haptic information (e.g., feeling the force arising from the virtual springs based on the cursor movement of the partner as shown in **Figure 1**). The experimental setup includes two backdrivable haptic devices with two degrees of freedom to provide force feedback to

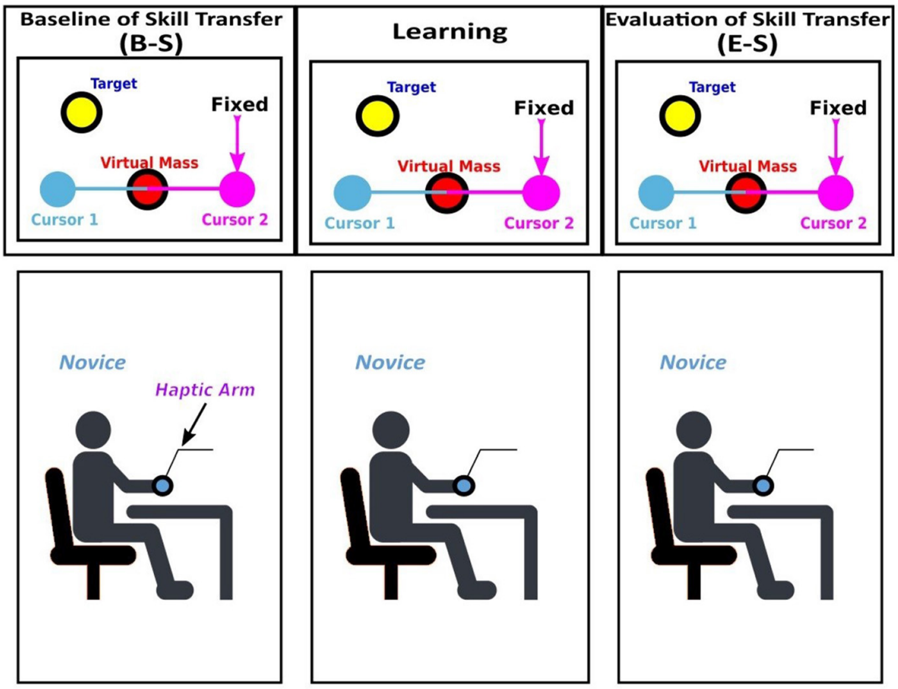

FIGURE 2 | Experimental protocol; the structure of the virtual tool and the experimental phases for the *Alone* group. Baseline of Skill Transfer (B-S), Learning and Evaluation of Skill Transfer (E-S). In each phase, the position of cursor 2 (purple circle) was fixed at a certain location and the cursor 1 (blue circle) which was correlated with motion of the end-effector of the haptic arm. The novice participant was asked to move a virtual mass (red circle) to the target position (yellow circle) as a single by using the haptic arm.

participants to simulate the haptic tool for a given task. Through the haptic tool, they can interact with each other haptically. Encoders (HEDM-5500 Incremental Encoder) were attached to each joint to measure the position of the participant in the virtual environment and actuators (RE25 Maxon DC Motors) to generate forces to simulate the forces of virtual springs. Real-time control of the system was implemented with UDP Ethernet connection between Host PC and xPC Target by using MATLAB-Simulink software package (the Mathworks Inc., MA, USA).

The experiment was set up in two separate identical rooms equipped with a display, PC, and a haptic arm, and performed in two configurations (see **Figure 1**): single configuration to investigate skill learning and paired configuration for adaptability. As shown in **Figure 1**, in both configurations, they received the same visual feedback on the computer screen in which two joint cursors (blue and purple circles) and virtual mass (red circle) were presented. The motion of these two cursors was correlated with the motion of the end-effectors of the haptic interfaces as shown in **Figure 1**.

To assess the motor performance of the single novice participants in the *N-N* and *N-E* group (**Figure 1**), or to train oneself as a single in the *Alone* group (**Figure 2**), in the single configuration, the position of the cursor 2 was fixed at a certain location so that the single participants can control the cursor alone to bring the virtual mass to the target position. The novice participants were asked to perform a motor task as an individual by controlling cursor 1 which was correlated with a motion of the end-effector of the haptic arm. On the other hand, to assess the adaptability to others of the novice participants in the N-N and N-E groups, or to train the novice participants in the N-N and N-E groups, the novice participants were paired with a preassigned partner who sits in the next room.

In the study, the participants were asked to move a joint cursor (a 10 kg mass, visualized as a red circle on the screen) from a home position ($[x_0,y_0]$=[0,0]) to a randomly placed target as quickly as possible by controlling the robotic arm as a single or with their partner. Under this instruction, they must control the two cursors which are virtually connected to the virtual mass under an external unknown force field. The target appeared at one of eight locations equally spaced at 45 degrees on a circle with a radius of 60 around the home position of the joint cursor ($[x_0,y_0] = [0,0]$) in each trial. Successful target capture was adjusted as simply crossing the boundary into the target. The end-effectors of the robotic arms representing the blue and purple cursors were attached to the virtual mass *via* non-linear virtual springs generating two force vectors ($\vec{F}_{c1}$ and $\vec{F}_{c2}$). To simulate the motion of a virtual mass with enough accuracy, the force of the virtual springs was calculated by considering two stiffness factors as ($k_1 = 148$) and ($k_2 = 1480$). L_1 and L_2 indicate the distance between the virtual mass and cursors (cursor 1 and cursor 2, respectively). Also, an external force field ($\vec{F}_{ext}$) was applied to the virtual mass to simulate the unknown external force field for a motor learning task; the motion of the virtual mass in the virtual environment was affected by the force field.

The stiffness factor (k_{ext}) was set as 596 for the external force field.

$$\vec{F}_{ext} = k_{ext} \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} x_m - x_0 \\ y_m - y_0 \end{bmatrix}$$
$$\vec{F}_{c1} = k_1 L_1 + k_2 L_1^2 \tag{1}$$
$$\vec{F}_{c2} = k_1 L_2 + k_2 L_2^2$$

These forces ($\vec{F}_{ext}$, $\vec{F}_{c1}$, and $\vec{F}_{c2}$) were used to drive a mass (M)/damper (B) system (in 2 DoF).

$$M\frac{d^2\vec{p}_m}{dt^2} + B\frac{d\vec{p}_m}{dt} = \alpha\vec{F}_{ext} + \vec{F}_{c1} + \vec{F}_{c2} \tag{2}$$

The experiment consists of five phases with three sessions: familiarization session (FS), training session (TS), and wash-out session (WS). The external force field was applied in the TS whereas the force was omitted during the FS and WS. Thus, α was used as a coefficient to activate or deactivate the external force field ($\vec{F}_{ext}$) in the MATLAB program depending on the session. Namely, α was set as 1 in the TS whereas it was 0 in the FS and WS.

2.4. The Phases

The experimental protocol was set in five phases for the *N-N* and *N-E* groups (**Figure 1**) and three phases for the *Alone* group (**Figure 2**). All experimental phases consist of three sessions: (1) FS in which the participants were familiarized with the task without the effect of the external force field, (2) TS in which the participants were trained by performing the task under the external force field, and (3) WS in which the external force field was ignored to erase the learned motor skills (i.e., internal model of the partner). Each session consists of a number of target-set (TS) including eight trials, and each trial consists of a movement to bring a joint cursor from the home position to the target.

As shown in **Table 1**, the experimental paradigm includes five phases for the *N-N* and *N-E* groups (see **Figure 1**): The Baseline of the Skill Transfer (B-S) phase which indicates the individual baseline performance of each novice consists of one set of FS and two sets of TS. The Baseline of Adaptability (B-A) phase which can be considered as the baseline performance of the paired participants includes two sets of FS and one set of TS. As a next phase, the Learning phase including two sets of FS and 30 sets of TS was performed with another preassigned novice or with an expert to learn the cooperative task under the external force field. The novices in the *N-E* group performed the Learning phase with the expert whereas in the *N-N* group the participants paired with a new novice. For instance, as shown in **Table 1**, participant N_1 executed the cooperative task with N_4 instead of N_2 in the Learning phase. Evaluation of Adaptability (E-A) phase which was performed as a pair to evaluate the individual adaptability of the novice participants includes two sets of FS, six sets of TS, and two sets of WS, respectively. The B-A and E-A phases were performed with the same pairs, namely if the B-A phase was executed by N_1 and N_2, the E-A phase was executed by the same participants e.g., N_1 and N_2. Last, Evaluation of Skill Transfer (E-S) phase including four sets of TS was performed as an individual.

For the *Alone* group (**Figure 2**), the experimental paradigm consists of three phases, and each phase was performed individually without the interaction with another one. B-S and E-S were performed in the same way as in the *N-N* and *N-E* group, but the learning phase was also performed as a single. The primary study was the comparison of *N-N* and *N-E* groups, and the *Alone* group was set as a check-mark to ensure that no factors are inadvertently overlooked. Also, by employing the *Alone* group, it is aimed to find the difference between trained with someone and learning through practice by oneself. The whole experiment was performed in 1 day; 3 h including 1 h break in the *N-N* group, 2 h including 45 min break in the *N-E* group, and 1 h with 15 min break in the *Alone* group. To prevent fatigue in the participants, there is a 15 s break between each target set (eight trials), 5 min break after each 10 target set, and, also, after each phase, there is a 30 min break.

To evaluate the motor learning to use the haptic tool under the unknown environmental dynamics and adaptability to a new novice participant, first, the B-S and E-S phases were compared to investigate how the novice participants can learn a new skill e.g., to practice by oneself, or with another novice, or with an expert. Second, the paired performances in the B-A and E-A phases were compared with the motor performance with a new novice in order to understand the adaptability to a new novice participant under the effect of corporation during the Learning phase.

2.5. Analysis and Statistics

To investigate the relationship between skill learning and adaptability within the motor learning paradigm, the performance of the participants was characterized by using three parameters (De Santis et al., 2014; Zenzeri et al., 2014; Mireles et al., 2017): (1) time to target (time duration to bring the virtual mass to the target position), (2) effort index (applied force to bring the virtual mass to the target), and (3) trajectory length (the length of the pathway followed by the participants to bring the virtual mass to the target). To quantify the motor learning and adaptability, using these parameters, two evaluation points were selected, namely, (1) the last set of TS in the baseline phase and (2) the first set of TS in the evaluation phase. To investigate the effect of training with a novice or an expert on motor learning, the two evaluation points were selected as the last target-set (TS) before the dyadic interaction and the first TS after the dyadic interaction. To evaluate the effect of the interacting partner during the Learning phase on adaptability to others, the evaluation points were selected as the last TS before the Learning phase and the first TS after the Learning phase. This means we compared the last TS of Baseline of Skill Transfer (B-S) phase and the first TS of Evaluation of Skill Transfer (E-S) phase to assess the skill learning and the last TS of Baseline of Adaptability (B-A) phase and the first TS of the Evaluation of Adaptability (E-A) phase for the adaptability. All analyses were performed by using SPSS and MATLAB software. A normality test (The Shapiro-Wilk test) was used to determine whether the samples were normally distributed (Royston, 1983) before the analysis. Wilcoxon Signed-Rank Test or a Paired-sample t-test was applied to evaluate the performance of the experimental groups. The significance level was set to 5%.

3. RESULTS

As shown in **Figure 1**, in the *N-N* and *N-E* groups, the participants experiments consist of five phases in which the Baseline of Skill Transfer (B-S) and Evaluation of Skill Transfer (E-S) phases were performed sequentially to study the motor learning of the individual participants induced during the Learning phase. In the B-S and the E-S phases, the novice participants performed the task on their own without a partner to evaluate the motor learning. When comparing the last TS of the B-S phase and the first TS of the E-S phase, we found that the average of time to target (see **Figure 3A**) showed a significant decrease between the B-S and E-S phase in the *N-N* groups ($p = 0.0020$), however, not in the *N-E* groups ($p = 0.0781$). The decrease in time to target indicates the motor learning. This means that the novice in the *N-N* group has learned motor skill, i.e., how to control the haptic device under the unknown external field.

Also, it is important to note that, when changing the evaluation points in terms of skill learning, there is no difference in the results. For instance, when comparing the first TS of B-S and the first TS of E-S, there is a significant decrease in time to the target of the N-N group ($p = 0.00098$), however not in the N-E group ($p = 0.3125$). The result is the same when comparing the first TS of B-S and the last TS of E-S (N-N: $p = 0.0244$; N-E: $p = 0.1484$) or the last TS of B-S and the last TS of E-S (N-N: $p = 0.0137$; N-E: $p = 0.1094$).

When comparing the length of the trajectory (see **Figure 3E**), there is a significant difference in the *N-N* groups ($p = 0.0371$), however, no difference in the *N-E* ($p = 0.0625$) groups. When analyzing the effort index, the results corresponded to the previous results obtained by comparing the time to target and the length of the trajectory. It means that there is a significant decrease ($p = 0.0210$) in the effort index of the *N-N* groups (**Figure 3C**). Those results indicated that as the participants learned the task through the adaptation to the external force field, they explored the unknown force field to find the shortest pathway for a given task, which resulted in a decrease in the length of trajectory as well as a decrease in the time to target and effort index. This means that a novice participant can learn a new skill (to manipulate a tool under the unknown force field) with another person who has the same skill level through haptic interaction, i.e., mutual skill learning between two persons with the same skill level. However, on contrary to a common sense, skill transfer from an expert to a novice participant did not occur.

As a next step, we analyzed the dyadic performance of the *N-N* and *N-E* group by comparing the time to target, the effort index, and the length of trajectory in the Baseline of Adaptability (B-A) phase and the Evaluation of Adaptability (E-A) phase to evaluate the degree of the adaptability to a new partner. Here, the last TS before the Learning phase and the first TS after the Learning phase were used for evaluation. When applied a paired-sample t-test, the significant difference was seen in *N-N* groups ($p = 0.0332$), not seen in *N-E* groups ($p = 0.5576$). The average of time to target (**Figure 3B**) showed a decrease between the B-A and E-A phases in the *N-N* groups (B-A: 3.51 ± 0.57; E-A: 2.17 ± 0.48) as well a slight increase in the *N-E* groups (B-A:3.48 ± 0.18; E-A: 3.86 ± 0.95). The largest decrease in time to target (38.78 %) was found in the *N-N* group (**Figure 4**). In addition, when analyzing the length of trajectory in terms of adaptability (**Figure 3F**), the significant difference was seen in the *N-N* groups ($p = 0.0320$), not seen in the *N-E* groups ($p = 0.1329$). This result is consistent with the previous result (**Figure 3B**) obtained by comparing the time to target. In summary, the participants in the *N-N* group could induce better performance in adaptation to a new partner rather than those in the *N-E* group. That is to say, regarding skill learning and adaptability, the best improvement was found in the *N-N* group where the skill level was matched in the novice-to-novice interactions.

In order to understand whether the novice participants can learn the motor skill under the unknown environment on their own (learning as a single participant throughout), without the dyadic interactions (with another novice or the expert), the same motor task was also performed individually without the dyadic interaction in the Learning phase by fixing one of the cursors on the display. This group (practicing alone) serves as a reference group to make a comparison with other two groups with the dyadic interaction (N-N and N-E group). As shown in **Figure 4**, practicing in the *N-N* group (38.78% decrease in time to target) is the most advantageous option to learn motor skills. Also, practicing alone (37.75%) is better than practicing in the *N-E* group (19.16%).

4. DISCUSSION

Human-human interaction in which your action affects the others, and the action of the others affects your action relies on continuous sensory feedback. The haptic sensory feedback being a channel for the mutual sharing of human intentions enables to achieve cooperative tasks.

We found that the best motor learning was induced in the N-N group, and the adaptability to others was best induced in the N-N group. This means that, according to our hypothesis, in peer-to-peer learning, adaptability to others could lead to the motor learning of the new tool under the unknown environment.

Previous studies (Ganesh et al., 2014; Mireles et al., 2017) using physical interaction based on haptic sensory feedback have shown that practicing with a partner is more advantageous than the individual practice to learn a task through unknown environmental dynamics. In our study, evaluating the performance as a single, the paired performance (learning the task together with the partner) showed better motor learning than the case of learning the task as a single participant. This result is consistent with the previous studies stating "two is better

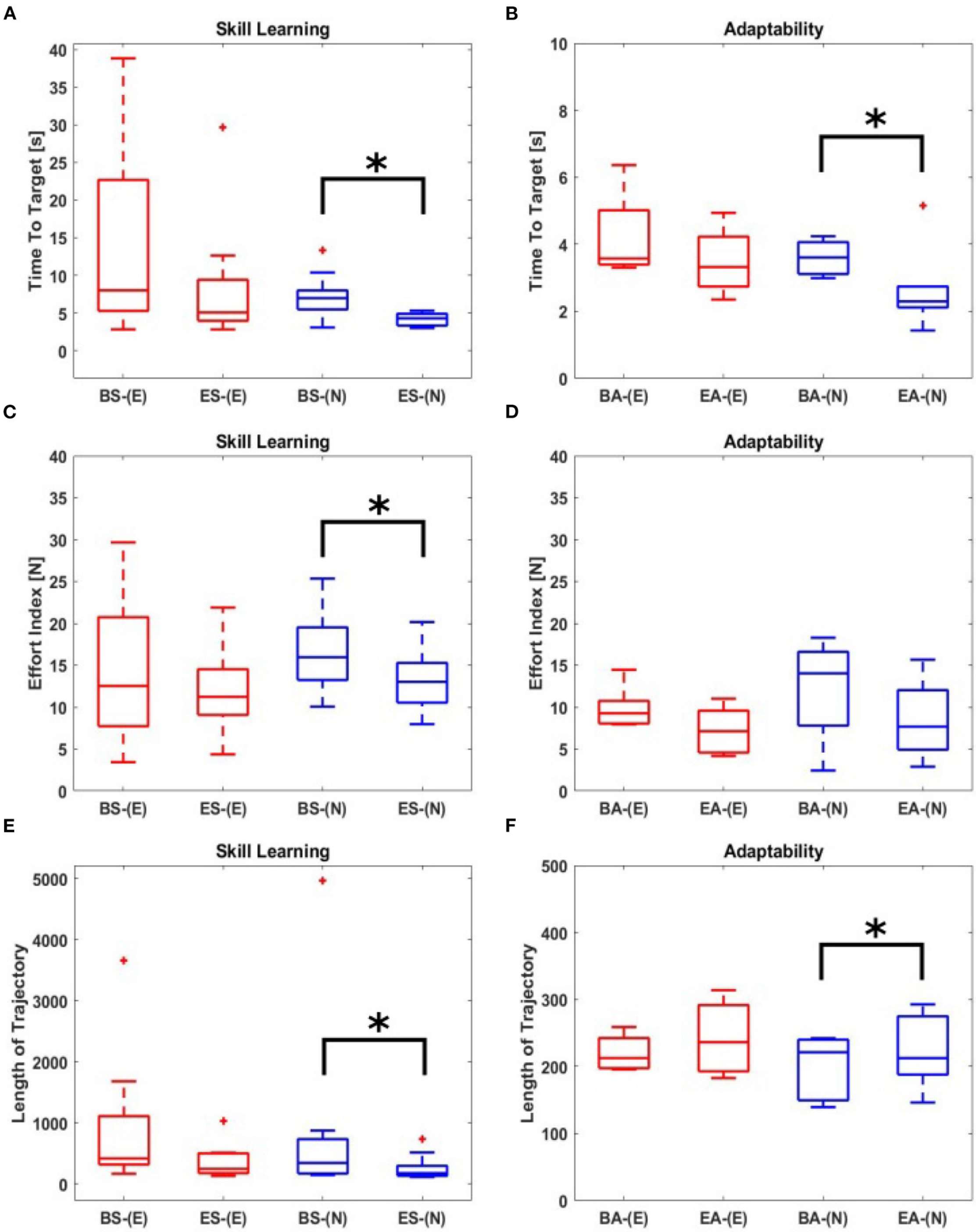

FIGURE 3 | Summary of performance measures: experimental groups: *N-N* or *N-E*. Red box plots indicate the participant was paired with the expert. Blue box plots indicate the participant was paired with another novice. Asterisks denote significant differences ($p < 0.05$). "skill learning"; time points: the last TS of B-S [BS-(N) for *N-N* group and BS-(E) for *N-E* group] and the first TS of E-S (ES-(N) for *N-N* group) and ES-(E) for *N-E* group]; **(A)** "time to target" - N-N: $p = 0.0020$; N-E: $p = 0.0781$. **(C)** "effort index" - N-N: $p = 0.0210$; N-E: $p = 0.6406$. **(E)** "length of trajectory" - N-N: $p = 0.0371$; N-E: $p = 0.0625$. "adaptability"; time points: the last TS of B-A [BA-(N) for *N-N* group and BA-(E) for *N-E* group] and the first TS of E-A [EA-(N) for *N-N* group and EA-(E) for *N-E* group]; **(B)** "time to target" - N-N: $p = 0.0332$; N-E: $p = 0.5576$. **(D)** "Effort index" - N-N: $p = 0.1943$; N-E: $p = 0.3279$. **(F)** "Length of trajectory" - N-N: $p = 0.0320$; N-E: $p = 0.1329$.

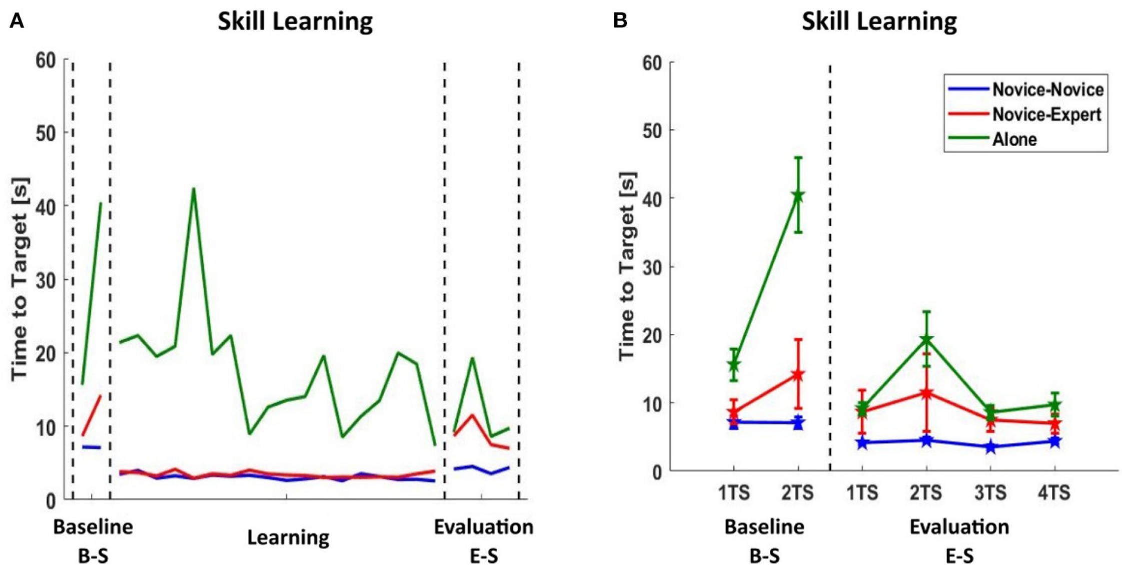

FIGURE 4 | Comparison of an average of Time to Target in terms of skill learning in second (the duration to bring the virtual mass to the target position). *N-N* (blue), *N-E* (red), or *Alone* (green) - **(A)** Average variation of Time to Target between the first and the last target set in the three phases of the experimental protocol; baseline (B-S), learning and evaluation (E-S) phase in order. **(B)** Average of Time to Target in each target set (TS) of baseline (B-S) and evaluation (E-S) phase. The Baseline phase includes two TS, and the evaluation phase includes four TS. The dispersion bars represent the SE and are not shown on **(A)** to highlight the trend.

than one" (Ganesh et al., 2014; Mireles et al., 2017). However, in their study, two participants are not controlling the joint cursor, thus, not being aware of the mutual interactions. In addition, practicing with another beginner rather than an expert is better to learn a task and to improve the individual performance (Ganesh et al., 2014; Mireles et al., 2017). A recent study (Mireles et al., 2017) showed that the skill learning is possible through interaction with an expert in case of having prior experience with the task.

Imagine, you are asked to perform a motor task with your partner under unknown environmental dynamics. In such a case, there may be a dual instability to define the basis of the guiding force, e.g., partner or environmental dynamics. To date, the studies (Ganesh et al., 2014; Mireles et al., 2017) focused on the adaptation to the environmental dynamics, but "how a human adapts to a new partner in a cooperative task" still remains an unclear issue. In this study, we first investigated the effect of training with an expert or a novice partner on motor skill learning by utilizing the widely used paradigm (Mireles et al., 2017) and as a novel paradigm, we studied the ability to adapt to a new partner (adaptability). We hypothesized that if adaptability to others can be induced while attempting to achieve a common goal, motor learning under the unknown environment would occur simultaneously.

Our experimental results (**Figure 3**) demonstrated that practicing with another beginner during the Learning phase allows for skill learning through the mutual interaction with a partner. It is normally helpful to have expert guidance while learning a new skill, but we showed that the *N-N* group is better to learn skills when compared to the *N-E* group. Therefore, we next examined the reason for non-being skill transfer from the expert to the novice in our study. To this purpose, we analyzed the trajectories and the movement smoothness of the virtual mass controlled by the participants in the *N-N* and *N-E* groups in the Learning phase as shown in **Figure 5**. The results showed that the participants in the *N-N* group followed more complicated and longer trajectories (**Figure 5B**) than those in the *N-E* group (**Figure 5A**). When analyzing the sum of trajectory curvature (**Figure 5C**), which plays an important role in the analysis of point-to-point trajectories (Morasso and Ivaldi, 1982), the *N-N* group showed higher curvature (normal distribution with mean $= 7.38 \times 10^5$) than *N-E* group (mean $= 4.14 \times 10^5$). In addition, the number of peaks in speed (**Figure 5D**), which is one of measure of the movement smoothness (Rohrer et al., 2002), significantly decreased in the *N-N* group ($p = 0.0048 < 0.05$). A decrease in the number of peaks in speed means an increase in movement smoothness, which shows, also, there is motor learning (Balasubramanian et al., 2015). When analyzing the distribution of the number of peaks across all trials in the Learning phase (**Figure 5E**), the *N-N* group has fewer peaks (a normal distribution with mean = 84.59) than the *N-E* group (mean = 121.20). In addition, when analyzing the trajectories followed by each participant in the Alone group, the correlation coefficient increased between the B-S and E-S phase, and the correlation is closer to 1 in the E-S phase when compared to B-S phase (**Figure 6**).

It can be summarized that the novice participants who are paired with another novice in the Learning phase could have more experience with the task by exploring the unknown external force field during the Learning phase. Thus, when doing the task

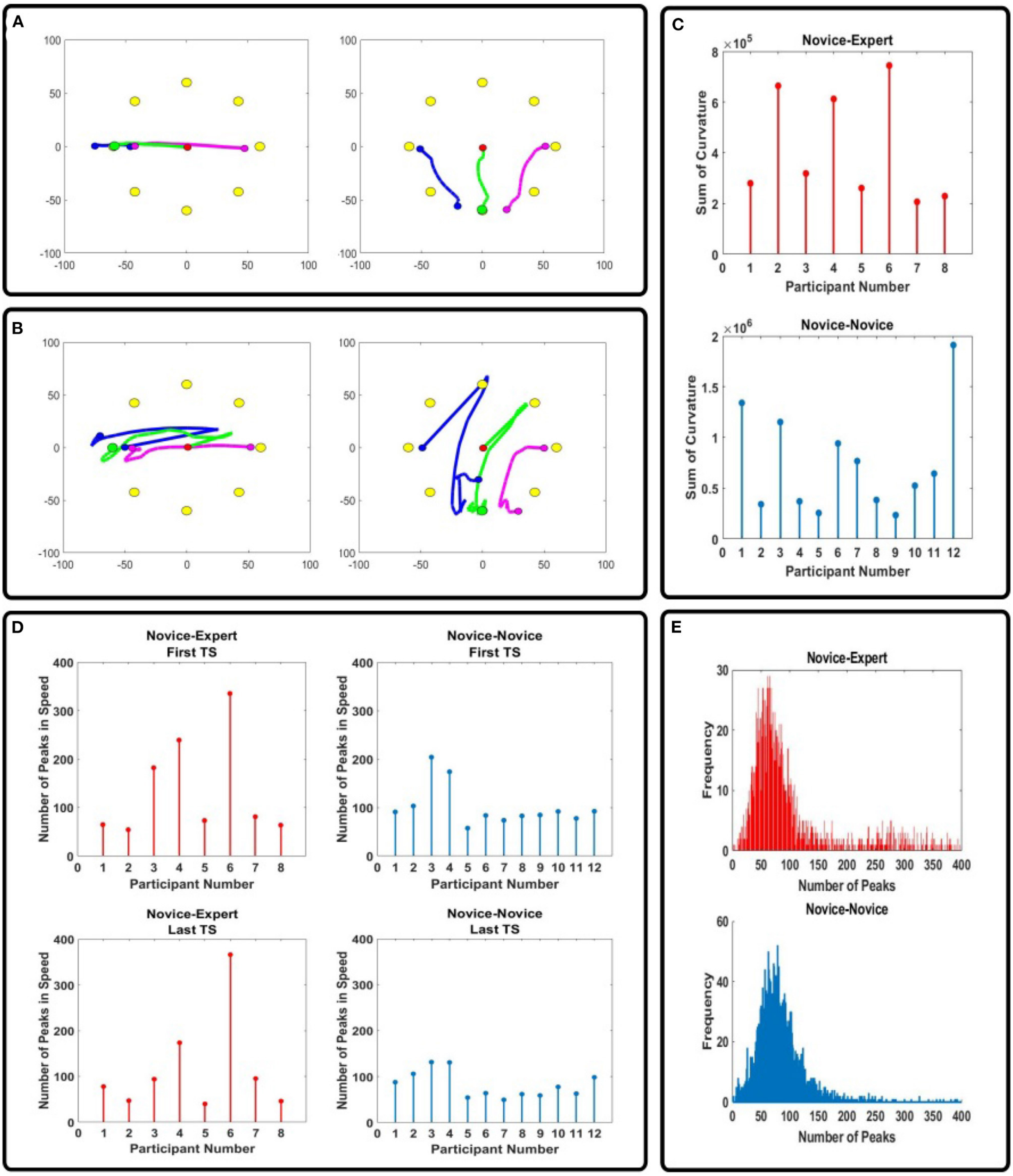

FIGURE 5 | (A) Samples of the trajectories generated by *N-E* group in the Learning phase. **(B)** Samples of the trajectories generated by the *N-N* group in Learning phase. Green circle shows the final position of the virtual mass. After completing the task, the participants were asked to bring their cursors (blue and purple circles) to the starting point which was set as [−50,0] and [50,0]. The blue and purple line indicate the trajectories generated by the participants, and also the trajectories of the virtual mass is shown with the green line. **(C)** Sum of the curvature of the cursor trajectory during the Learning phase for each participant. **(D)** Change of the number of peaks in velocity between the first TS and last TS of the Learning phase. **(E)** Distribution of the number of peaks across all trials in the Learning phase.

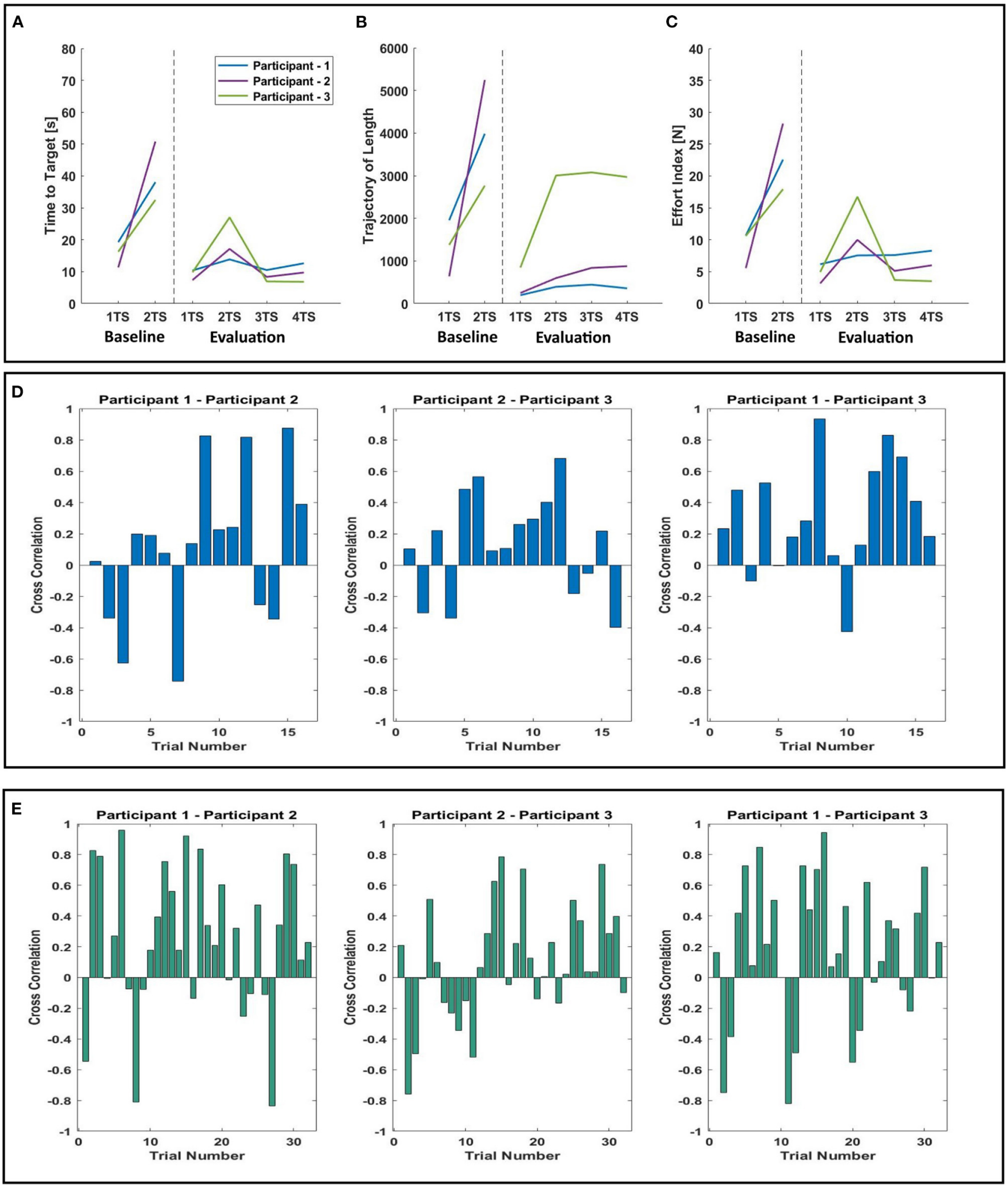

FIGURE 6 | Summary of performance measures of *Alone* group. **(A)** Comparison of time to target, **(B)** comparison of trajectory length, **(C)** comparison of effort index, **(D)** cross correlation of trajectories in the Baseline (B-S) phase, **(E)** cross correlation of trajectories in the Evaluation (E-S) phase.

alone in the evaluation phase, the participants could do the task more quickly, resulting in a significant decrease in time to target between the baseline and evaluation phase (**Figure 3**). Here, we can think of learning with another beginner as an example of "collaborative learning" (Dillenbourg, 1999), an educational approach in which two or more people make effort to learn the task together.

On the other hand, the novice participants interacting with the expert during the Learning phase could not have enough experience with the environmental dynamics which could be an obstacle to learning skills from the expert. Here, it is important to note that the expert must consider the point of view of the novice and ensure the feedback is in harmony with the novice's needs (Magill and Anderson, 2010). In conclusion, participants who performed the task with another novice can have more experience with the task due to the time for exploration (**Figure 5**), so they showed better results in skill learning.

In cooperative tasks, the other thing to be considered is predicting the motion of the partner at the next step. For such prediction, an internal model of the partner is necessary to simulate the motion of the partner in the action-perception loops. If one builds up the generalized internal model, one can adapt to a new partner and cooperate with them quickly to achieve a common task. Our results, being consistent with the hypothesis, indicate that novice-to-novice performance leads to mutual adaptability to others, which resulted in mutual skill learning. However, there is no skill transfer from an expert to a novice because of the lack of experience in the novice participants during the Learning phase, resulting in a lack of adaptability to a new partner. To summarize, more experience eases to explore the environmental dynamics and so find the internal model of the partner in the cooperative task. We speculate that the accumulation of the prediction errors defined as the difference between predicted and actual feedback can help in training individuals to develop the internal models of others. The prediction error allows a person to explore the "free energy" basin. Free-energy, which is a function of sensory and internal states, can be minimized through action (Friston, 2010). Minimizing free energy may increase the accuracy of predictions while performing the cooperative tasks.

In the activities requiring coordinated behaviors, it is important to explore the interpersonal synergies between the interacting people (e.g., adaptation between players and between a player and a conductor during ensemble music performance) to find the best way of skill learning. Our results are very informative for training session in the activities requiring cooperation and coordination such as dance (Chauvigné et al., 2019) or ensemble music performance (Wing et al., 2014). In modern society, though development of the industrial robots largely contributed to the manufacturing process of the products, for safety reasons, their work-space has been isolated from human operators. Thinking about the future of robots working in our daily environment, it is important to understand the nature of human-human interaction to create the human-machine interface which can be implemented in robots making a contact with humans for elderly care or rehabilitation (Sawers and Ting, 2014; Nasr et al., 2020). Thus, the principles of human-human interaction would facilitate the design of human-robot interfaces, "having ability to communicate naturally with humans as if humans do with each other" (Shimoda et al., 1999). That is to say, our findings will be useful to further investigate motor learning during human-human interaction (McNevin et al., 2000) and, also, to develop the human-machine interface which can be implemented in the control system (Sawers and Ting, 2014; Sakamoto and Kondo, 2015; Nishimura et al., 2021).

5. CONCLUSION

Our results showed that the experience with another novice partner during the Learning phase plays a significant role in adaptation to a new partner (adaptability) as well as a skill learning under an unknown field. That is to say, learning a motor task together with another novice through exploration of the unknown environmental dynamics led to higher adaptability for a person and to the best motor learning for a given task. We suggest that peer-to-peer learning would work, as they have more chances to explore the unknown external field, resulting in increasing the adaptability to others and learning the necessary skill set to control the device under the unknown field.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Ethics Committees of the University of Reading (No. SBS18-19 28). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

TK and YH conceptualized the research project. OS did participant experiments, analyzed the data set, and discussed the results with WH, TK, and YH. All authors contributed to writing a draft of the paper and read and approved the final manuscript.

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Chapter 5

Simultaneous against to Sequential Learning via Haptic Interaction

While learning skills through interaction with others, humans can face a dual instability arising from the environment and the interaction with a partner. How can humans deal with dual instability caused by partner and environmental dynamics within a cooperative motor task? This chapter addresses an issue of how to overcome dual instability. It is important to note that subjects interacted with their partner through only haptic feedback. We hypothesized that separation of dual dynamics would result in skill learning. This result is in the line with the hypothesis that it is necessary to separate partner dynamics from environmental dynamics to allow for simultaneous learning. Additionally, mutual haptic interaction is of prime importance for simultaneous learning. Our findings, which emphasized the importance of mutual haptic interaction for skill learning, would provide possible new insights into training in education, sport or rehabilitation.

To date, much of the literature on motor skill learning have identified outcome measures as time to target, force or trajectory (Appendix C). As in chapter 4, the performance of the participants was characterized by evaluating the time to target and trajectory smoothness. Also, haptic interaction was the only mode of communication between the paired participants in this study. Thus, the force applied by each participant was evaluated as an outcome measure. The experimental setup was same as shown in chapter 4 (see Appendix A for details).

This chapter has been submitted to Scientific Reports. The author of this thesis, Ozge Ozlem Saracbasi, who is the first author of this journal paper, did participant experiments, analyzed the data set, and discussed the results with the co-authors, William Harwin, Toshiyuki Kondo and Yoshikatsu Hayashi.

Simultaneous Learning against to Sequential Learning via Haptic Interaction

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ABSTRACT

From a parent assisting to their child to use a spoon, to a physical therapist helping stroke patients to relearn walking, haptic assistance via haptic feedback plays an important role in skill learning. It is known that skill learning is associated with learning unknown dynamics within the interaction. For instance, while learning skills with a new partner under unknown environmental dynamics, humans are specifically exposed to two unknown dynamics: partner dynamics and environmental dynamics. Although recent studies have focused on skill learning mostly through adaptation to environmental dynamics or partner dynamics, much less is known about 'dual instability'. Is it possible to deal with dual instability? We developed a new paradigm in which we asked paired participants to control the joint cursor, representing the interaction dynamics e.g. partner, own self and environment. Note that the haptic device controls the joint cursor through two springs connected to cursors controlled by the paired participants, however, only the joint cursor was made visible. As the environmental dynamics exert the forces on the joint cursor, dual instability for the participants was realised. Under the cooperative task, we assessed whether one can learn to bring the joint cursor to the target with a partner. We examined skill learning under four conditions: (1) cooperative sequential learning, (2) simultaneous learning of partner and environmental dynamics, (3) individual sequential learning, (4) individual learning. Skill learning were quantified using time to target, trajectory smoothness and force. Experimental results suggested that if two-people interact actively (i.e. move the joint cursor together), there could be a separation of dual dynamics, which result in skill learning. The order of the unknown dynamics is not matter (e.g. sequential or simultaneous). There could be skill learning even though exposed to the most difficult condition, in simultaneous learning.

Introduction

Motor skill learning is crucial for humans to perform daily living activities independently or through interaction with others. From birth, humans learn a variety of motor skills through the interaction with someone (e.g. parent, teacher or coach) using auditory[1], visual[2], haptic feedback[3] or a combination of them[4]. For instance, babies learn how to use a spoon or children learn how to walk through the interaction with their parents. In rehabilitation, patients (re)learn motor functions through the interaction with physical therapists[5]. Physical interactions between children and parents or between therapists and patients is provided through haptic feedback.

Haptic feedback plays a key role on motor skill learning process, especially in infants by enabling them to gather information about unknown dynamics in their surrounding environment to be used to explore the environment[6]. The technological advancements paved the way of robotic haptic interfaces[7,8], providing bi-directional exchange of information between a person and their surrounding environment[8] or between two interacting persons[9]. Recent studies[7,9] employing robotic haptic interfaces outlined that dyads showed better performance than individuals. Another study conducted by Takagi et al.[10] showed that individuals' performance improved with an increase in the size of the group. Also, Ganesh et al.[9] emphasized that dyadic interaction is more effective in a motor task regardless of the interacting person's performance (even with a partner having worse performance). Numerous studies on skill learning have attempted to explain the influence of the roles on dyadic performances, such as novice-expert[7,11] or leader-follower[5]. An example of leader-follower[5] can be seen between a physical therapist and a patient in rehabilitation, such that the physical therapist takes the role of leader to assist the patient, who follows the therapist to do the movements. Depending on the skill level[11], the physical therapist can be considered as an expert, and the patient as a novice in the beginning of treatment. The previous studies[7,9,11–14] showed that having practiced with a similarly skilled person is more advantageous than practiced with an expert.

It is important to note that skill learning relies on learning unknown dynamics within the interaction, such as partner or environmental dynamics. For instance, in a dyadic reaching task, a learner makes an attempt to explore the unknown dynamics[7,15] (e.g. feeling the force from the interaction with a partner in the presence of external force fields in the environment), which would result in skill learning. Our experimental paradigm differed from previous studies in two aspects. First, Takagi and colleagues[9,16] designed an experimental paradigm in which two-people performed a tracking task independently. Their hands were virtually connected to each other while performing the task. Also, the subjects saw their own cursor position, not their partner's cursor on the display. The subjects did not share the same virtual environment, and the experimental task was not a cooperative task, so it still remains unclear whether two participants under the cooperative task can work better. Second, Morasso's research team[7,15] employed a reaching task in which both of two participants see their own cursor and joint cursor on display. Visual information on cursor positions enable participants to learn the partner dynamics and the environmental dynamics affecting the joint cursor. The results are controversial because one can simply learn the dynamics of the partner by utilizing the visual information of the cursor on display. Therefore, we defined a new paradigm where the joint cursor is a true representation of the dual instability (environment + partner's dynamics).

In motor learning paradigm, one can predict the next motion of the partner based on the internal model of the environmental and partner dynamics. Here, internal model refers to an approximation of the unknown dynamics in the task[17,18]. Previous study conducted by Takagi et al.[16] suggests that visual information forms an internal model of the task, so one can estimate partner's target. Also, Mireles et al.[7] emphasized that haptic feedback is important to shape the internal model of the interaction dynamics in a motor task. There is still uncertainty, however, whether 'haptically' interacting subjects identify the emergence of self or partner dynamics under the environmental dynamics.

In action-perception loop based on the internal model, humans perceive the unknown dynamics within the interacting environment and act using multisensory integration of visual, auditory or haptic feedback. Some studies[9,15,19] suggested that the integration of visual and haptic feedback may be the reason behind the skill learning. On the other hand, some studies[20,21] indicated that pure haptic feedback is more effective in order to prevent the loss of attention. Haptic feedback is considered as a channel between two interacting people to negotiate their intentions mutually[15,22,23]. Previous studies[9,16] emphasized the importance of adaptation to partner's behaviour on skill learning through the interaction with someone. Also, it has been suggested that different order of practice leads to different knowledge structures[24]. However, these studies do not fully explain the principle behind the skill learning. 'How the order of unknown dynamics (e.g. environmental or/and partner dynamics) affect skill learning process' remains unclear.

We further investigated the order of unknown dynamics in skill learning by seeking an answer to the four following questions: Is it possible (1) to learn environmental dynamics with an interacting partner after familiarisation with the partner's dynamics? (2) to learn skills if exposed to unknown environmental dynamics with the presence of unknown interacting partner? (3) to learn partner's dynamics under environmental dynamics after familiarized with environmental dynamics individually? (4) to learn environmental dynamics alone (without a partner)?

In this study, we asked the subjects to manipulate a robotic arm to move the joint cursor to the specified target with their preassigned partner. We employed a novel experimental paradigm in which the position of the cursors controlled by the paired subjects and virtual springs were invisible. That is to say, in a paired performance, the subjects interacted with their partner through pure haptic feedback (i.e., there is no visual feedback related to the cursor position).

Results and Discussion

In contrast with previous studies[7,9,12,16] on skill learning where cursors represented their own individual motion and the joint cursor, to our end, we examined mutual skill learning by removing the visual information of oneself and partner (invisible cursors for Participant A and B). Thus, only the joint cursor (red circle) was shown on the display and controlled by the cursors through the virtual springs (also, invisible) as shown in Fig.1. In this way, the participants can interact with their partner through haptic feedback (feeling the force through the virtual haptic tool on the display). The haptic feedback to the hand itself was provided by the haptic device on the desk in Fig.1 (see the details in Methods). Motion of the joint cursor was simulated by the virtual mass which was affected from the external force field and the force arising from the virtual springs based on the partner's cursor movement.

In this study, we look for the necessary conditions for the paired participants to be able to learn the environmental dynamics as well as partner's dynamics such that the joint cursor can reach the target position in a shorter time. In summary, we study how the paired participants can overcome the dual instability under the mutual interactions.

To this end, the experiment was performed in four conditions as shown in Table 2:

1. Condition 1: Cooperative Sequential learning
    - Familiarize with partner dynamics.
    - Learn the environmental dynamics together with the familiarized partner.
2. Condition 2: Simultaneous learning
    - Expose to partner dynamics and environmental dynamics simultaneously

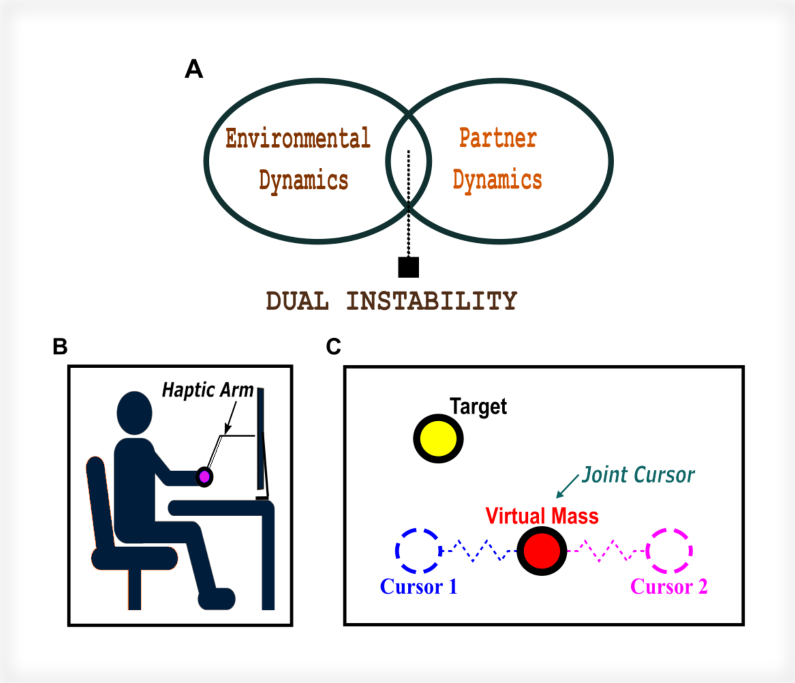

Figure 1. **(A)** An illustration of the experimental paradigm. Dual instability due to partner or/and environmental dynamics in a human-human interaction. **(B)** The experiment was set up in two identical rooms equipped with a PC, a display, and a haptic arm. **(C)** Experimental task. A virtual mass (red circle) was connected to two cursors (blue and purple circles) with virtual springs (blue and purple springs) and subjected to an external force field. During a trial, the cursors controlled by the participants and virtual springs were invisible on the display to remove the visual information related to the participants' own and their partner's cursor motion.

    - Remove environmental dynamics
3. Condition 3: Individual Sequential learning
    - Familiarize with environmental dynamics as an individual.
    - Familiarize with a new partner under familiarized environmental dynamics.
4. Condition 4: Individual learning
    - Learn environmental dynamics as an individual. No dyadic interaction.

Each condition consists of three main experimental sessions: Familiarization (FS), Training (TS) and Wash out (WS). In this study, skill learning[25] refers to the learner's progress in the motor task shown in Fig.1 as a result of training (i.e., the change in performance between FS and WS).

Within the experimental task, the participants followed point-to-point trajectories to move the joint cursor to the target (see a typical example in Fig.2). Thus, we performed trajectory analysis to assess the performance improvement due to training. At a first glance, the trajectory path was more complicated before training (Fig.2A) than after training (Fig.2B), which might be a sign of skill learning. Then, we calculated trajectory length for Condition 1 (Fig.2C) and Condition 2 (Fig.2D). When analysing sessions before and after training (FS and WS) using a paired t-test, both condition showed a significant decrease in trajectory length (Condition 1: $p = 0.0033$; Condition 2: $p = 0.0024$).

The other feature to analyze the point-to-point trajectories[26] is trajectory smoothness, so we calculated the number of peaks in velocity[27] and the sum of trajectory curvature (Fig3). As the velocity data did not have normal distribution, the analysis was done using the Wilcoxon Signed-Rank test (Fig3). When comparing FS and WS, a significant decrease was seen in Condition 1 ($p = 0.002$) and Condition 3 ($p = 0.049$), however, not in Condition 2 ($p = 0.16$). The decrease in the number of peaks in velocity indicates the skill learning[28].

To quantify skill learning in each condition, we calculated time to target (i.e. time to move the joint cursor to the target with a partner or alone). Statistical significance was analyzed using a paired t-test, of which all passed the Shapiro–Wilk normality test at the 5% significance level. As shown in Fig.4, the average of time to target showed a significant decrease between FS and WS in each experimental condition (Condition 1: $p = 0.044$; Condition 2: $p = 0.004$; Condition 3: $p = 0.002$; Condition 4: p

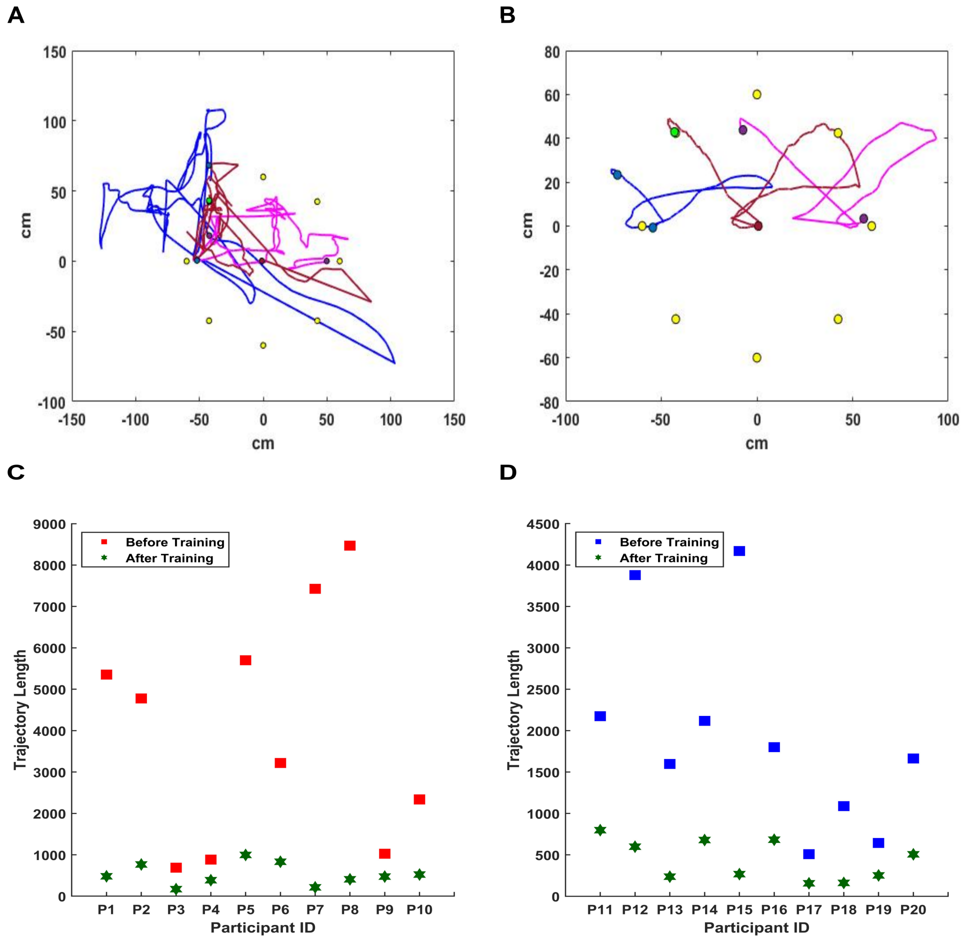

Figure 2. Trajectory analysis. A successful trial has been completed when the joint cursor (red circle) crossed into the target (yellow circle). The green circle and red line show the final position and trajectory of joint cursor, respectively. The blue and purple lines indicate the trajectories followed by paired participants. **(A)** Before Training session, there is no synchrony between the partner's trajectories. **(B)** After Training session, the partners applied forces in the same direction to move the joint cursor to the target. **(C)** and **(D)** show distribution of trajectory length. **(C)** Sequential learning condition. **(D)** Simultaneous learning condition. In both condition, each participant followed longer trajectory before Training compared with after Training. Sequential learning condition: $p = 0.0033$; Simultaneous learning condition: $p = 0.0024$.

= 0.002). When comparing the amount of overall decrease in time to target, the most decrease was observed in Condition 3 (individual sequential learning) and Condition 1 (cooperative sequential learning) with 80.1% and 79.2%, respectively. The decrease was 55% in Condition 2 (simultaneous learning) and Condition 4 (individual learning). The decrease in time to target indicates the skill learning. When comparing the first and last Training set (Fig.4), the significant decrease was seen in Condition 1 ($p = 0.02$) and Condition 3 ($p = 0.023$), as well. When characterizing the performance curve (learning curve) which is a common way to illustrate the performance, the time in the Training session decreased more sharply in Condition 1 and Condition 3 (Fig.6).

In Condition 1 (cooperative sequential learning) and Condition 2 (simultaneous learning), the whole experiment was performed with a partner and the number of training set was same. Therefore, specifically, Condition 1 and Condition 2 were chosen to highlight the differences between Simultaneous Learning and Sequential Learning. When comparing Condition 1 and Condition 2, throughout whole Training session, the mean of sum of trajectory curvature was higher in the Condition 1 (2.44×10^5) than Condition 2 (2.39×10^5). Also, the findings of the Wilcoxon Signed-Rank test revealed that there was a statistically significant difference between the first and last Training set in Condition 1 ($p = 0.026$), not in Condition 2.

Next, we measured the forces exerted by each participant (visualized as blue and purple vectors in Fig.5), and found the net force by calculating a sum of vector norms of these forces (red vector in Fig.5). As shown in Fig.5, the expected force

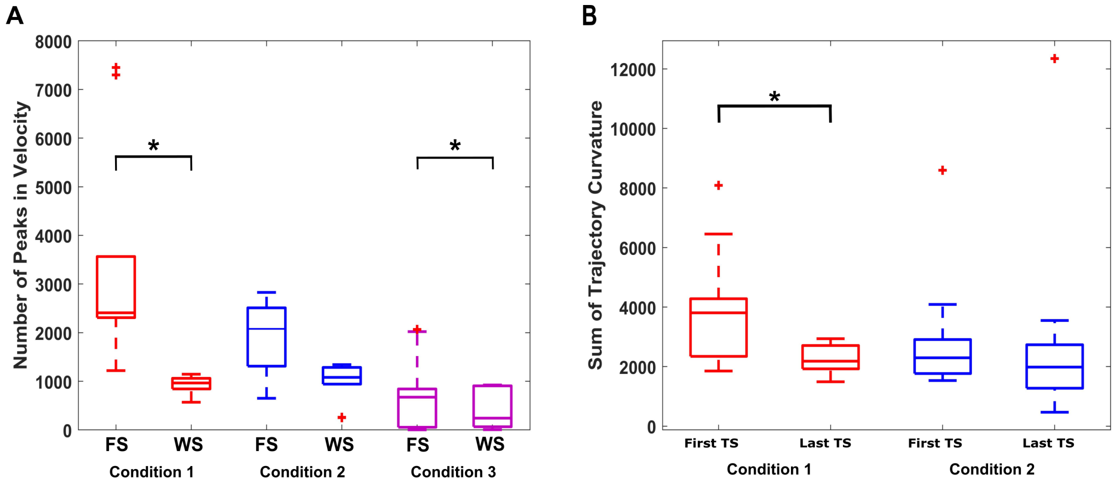

Figure 3. Evaluation of trajectory smoothness in 3 conditions: Condition 1 (cooperative sequential learning; red box plots), Condition 2 (simultaneous learning; blue box plots) and Condition 3 (individual sequential learning; purple box plots). Asterisks denote significant differences according to the Wilcoxon Signed-Rank test. **(A)** Number of peaks in velocity. Time points: FS (session before training) and WS (session after training). **(B)** Sum of trajectory curvature. Time points: First TS (the first set of Training session) and Last TS (the last set of Training session).

was determined as the desired force to move the virtual mass to the target in a straight way. We calculated the correlation between time and α (i.e. angle between the expected force vector and net force vector) in sub-movements. Sub-movements were extracted from participants' tangential velocity data[29]. The findings showed that time to target decreased associated with a decrease in the angle in the sub-movements.

In this study, haptic interaction (force interaction) was the only mode of communication between the paired participants. The participants negotiated their intentions with their partners via force signals. Thus, the success in the paired performance might depend on not only the participants' effort[7] during the negotiation process but also whether to feel force interaction. As shown in Fig.5, the force time series show an overlap such as between 2000 ms and 4000 ms, which might be due to the shared control of the task by utilizing haptic information channel (i.e., force interaction)[3]. To give a deeper comprehension of the haptic motor task execution, we calculated the average of each participant's contribution during the Training session. As stated in Table 1, the contribution of P7 and P8 was not equal in Condition 1, and also the contribution of P19 and P20 in Condition 2.

Moreover, at the end of the experiment, each participant was asked whether they felt haptic feedback while performing the task. The questionnaire showed that each participant felt the haptic feedback except for two participants in Condition 2 (P19 and P20).

Training session was performed in two different type (with / without external force) in Condition 1 and Condition 2. When comparing the average of time to target in the first Training session with the second one, time to target showed a decrease in each paired performance in Condition 1 (cooperative sequential learning). However, in Condition 2 (simultaneous learning), two dyads showed an increase in time to target (P13-P14 with an increase from 9.2 to 12.8 and P19-P20 with an increase from 11.9 to 12.5). The results suggest that in Condition 1 (cooperative sequential learning) the performance improvement is independent from the mutual interaction between the participants. On the contrary, in Condition 2 (simultaneous learning), the performance improvement depends on the interaction between the participants.

To clarify the results, we calculated the correlation coefficient between forces produced by the two participants in each sub-movement. As shown in Fig.5, the correlation decreased between FS and WS in Condition 1 (from 0.75 to 0.42). On the other hand, the correlation was approximately 0.5 in both FS and WS in Condition 2. Also, between the first and last target-set of each Training session, the correlation decreased in Condition 1 (cooperative sequential learning), however, increased in Condition 2 (simultaneous learning). In spite of the decrease in the correlation between force A and B in Condition 1, there is a skill learning. The result confirms that mutual haptic interaction is of prime importance for simultaneous learning.

In the light of the previous study[30], we, also, identified haptic states to further understand the force interactions. As can be seen from Fig.5, the percentage of Haptic State 4 (i.e. paired participants apply force above threshold at the same time) was found higher in Condition 1 than Condition 2 whereas the percentage of Haptic State 1 (i.e. none of participants applied force above threshold) was found higher in Condition 1. When comparing Haptic State 2 and 3 (i.e. one of participants applied force above threshold), in Condition 1 the rate is lower than Condition 2. It means that in Condition 1 (cooperative sequential

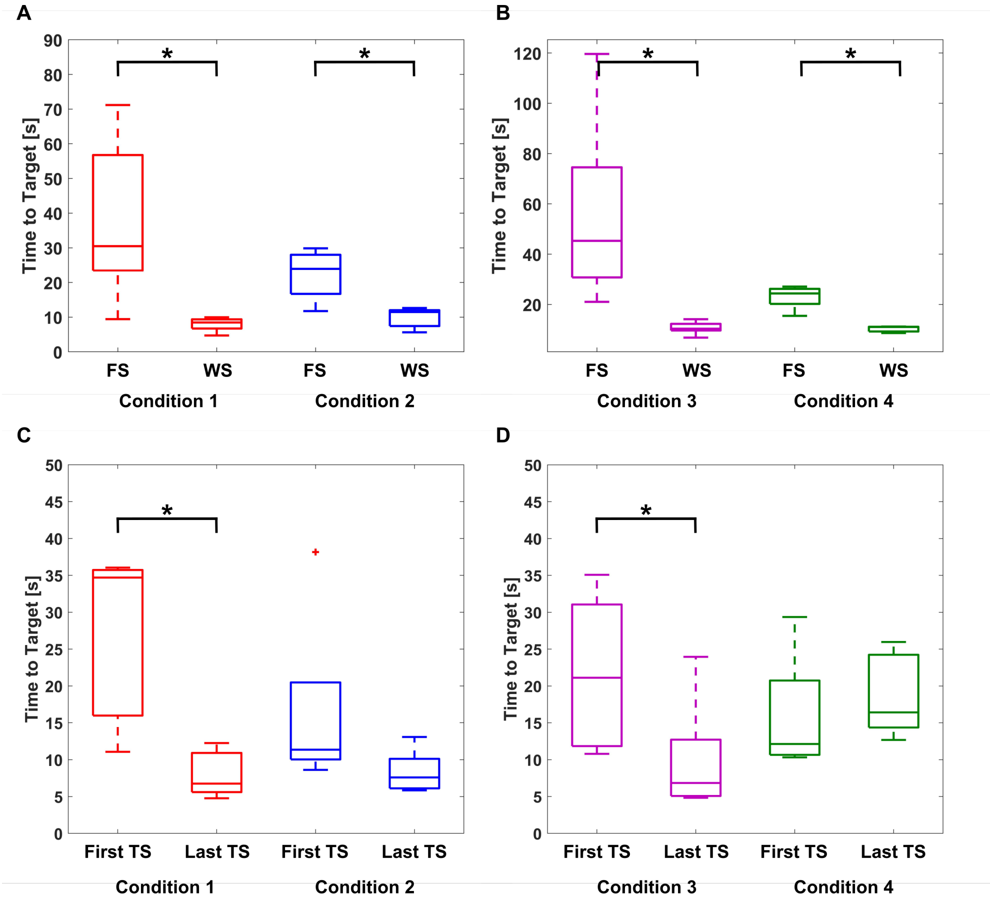

Figure 4. Evaluation of Time to Target. Experimental Conditions: Condition-1 (cooperative sequential learning; red box plots) in which participants first familiarized with partner dynamics and then exposed to environmental dynamics with the familiarized partner. Condition 2 (simultaneous learning; blue box plots) in which participants exposed to partner and environmental dynamics simultaneously. Condition 3 (individual sequential learning; purple box plots) in which participants first familiarized with environmental dynamics as an individual, and then learned partner dynamics under the familiarized environmental dynamics. Condition 4 (individual learning; green box plots) in which participants learned environmental dynamics as an individual. Asterisks denote significant differences ($p < 0.05$) according to a paired t-test. Time points: FS (Familiarization) and WS (Wash Out) to evaluate skill learning; first TS (first training set) and last TS (last training set) to evaluate the effect of Training session in the performance of the participants.

learning) each participant in a pair applied force at the same time, which may enable paired participants to interact with each other via force signals. On the other hand, in Condition 2 (simultaneous learning) one of participants in a pair applied force, which may cause the lack of force interaction between the participants.

Taken together, these results suggest that Condition 1 (cooperative sequential learning) or Condition 3 (individual sequential learning) appears to have a positive effect on skill learning, whereas others (simultaneous learning or individual learning) seem to result in less successful learning. Also, it is fundamental to have mutual active haptic interaction for simultaneous learning.

General Discussion

Motor learning plays an important role in many aspects of life including home, school, sport or occupations such as surgeon, physical therapist or pilot. Prior studies have noted the importance of haptic interaction on performance improvement such that experimental studies have shown that physical interaction improved skill learning even interacting with a worse partner[9]. Focusing on the usage of haptic feedback in real-life, many pilots have been trained in flight simulators, whereas surgeons have been trained using medical simulations[6].

Skill learning relies on exploration of unknown dynamics within the interacting environment such as partner or environmental dynamics. Recent studies[7,9,15,16] have examined the issue of 'dual instability' due to partner or environmental dynamics by

Table 1. Contribution of each participant in each pair through the Training sessions: (Condition 1 and Condition 2 consist of two Training sessions: TS without Force and TS with Force. The values above threshold (70%, determined empirically) are shown in bold to indicate the significance of the force interaction for the performance improvement.

Condition 1	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
TS *without* Force	35.9%	64.1%	67.8%	32.2%	**28.6%**	**71.4%**	**75.5%**	**24.5%**	41.3%	58.7%
TS *with* Force	35.6%	64.4%	**78%**	**22%**	43.5%	56.5%	**84%**	**16%**	41%	59%
Condition 2	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20
TS *with* Force	37%	63%	40.1%	59.9%	32.6%	67.4%	62.7%	37.3%	**13.8%**	**86.2%**
TS *without* Force	39.2%	60.8%	**30%**	**70%**	39.5%	60.5%	59.3%	40.7%	**21.4%**	**78.6%**

employing both haptic and visual feedback. The originality of this study is that it explores the principle of skill learning through 'solely' haptic interaction under unknown dynamics. The study used a novel experimental paradigm in which the position of the cursors controlled by the paired subjects and virtual springs were invisible whereas the joint cursor was visible on display. The key is that the joint cursor is a true representation of the environment and partner dynamics.

Notably, we found that sequential learning is more advantageous than simultaneous learning under haptic interaction. A possible explanation for this result might be that participants could not separate partner dynamics from environmental dynamics, which might be an obstacle in the learning process. This result is in the line with the hypothesis that it is necessary to separate partner dynamics from environmental dynamics to allow for simultaneous learning.

Additionally, we found that sequential learning of partner and environmental dynamics was more advantageous than simultaneous one. If subjects expose to two unknown dynamics (environmental dynamics or partner dynamics) simultaneously, they could not easily discriminate between them.

Also, it is fundamental to have mutual active haptic interaction for simultaneous learning. This result may be explained by the fact that mutual haptic feedback enhances the process of intention integration[22], which enables simultaneous learning. In contrast, within the passive interaction, learners having passive behaviour in a paired task exerted less effort, and so they could not explore unknown dynamics and form their internal model. The reason behind the passive behaviour[4,7] might be that presenting too much complexity in a learning task (e.g. exposure to unknown partner and environmental dynamics simultaneously) might discourage the learner[24]. Previous studies[9,16] indicated the importance of two-way communication in skill learning. Consistent with these studies, we highlighted that interactive haptic communication seems to be the main factor for the simultaneous learning. However, in sequential learning, there is no need for the mutual interaction.

Another important finding is that if one builds the internal model of partner's dynamics, one can learn environmental dynamics with the interacting partner. Considering the other case, if one builds the internal model of environmental dynamics, one can adapt to a new partner by estimating environmental dynamics in the task. In sequential learning, the performance improvement would depend on the order of unknown dynamics in the Training session. This study set out with the aim of examining the order of interaction dynamics being learned. Evidence suggested that in skill learning the order of items being learned affected knowledge structures[24]. The current study including two unknown dynamics to be learned have two experimental conditions to investigate sequential learning: (1) first learn partner dynamics, and then learn environmental dynamics. (2) first learn environmental dynamics, and then learn partner dynamics. Surprisingly, there was a slight difference when changing the order of partner dynamics and environmental dynamics. The findings showed that the performance improvement was lower in the case of learning first partner dynamics than the other condition (learning first environmental dynamics). It has previously been observed that force signals having a frequency of 20-30 Hz offer a meaningful perception[31]. This result may be explained by the fact that humans would have some filtering system for low and high frequency haptic interactions. It would seem that environmental dynamics might contribute to the low frequency haptic feedback and the partner dynamics might be the higher one.

Moreover, it is known that humans should learn basic skills before complex skills requiring expertise in these basic skills[32]. Namely, we can say that subjects in our study may approach the issue of dual instability as a complex skill, which prevented skill learning. Reducing the complexity through presenting the unknown dynamics in a sequence allows for skill learning.

To date, research on skill learning employed mostly visuo-haptic feedback to investigate human-human interaction in education, sports, or rehabilitation[4,7,16]. Our findings, which emphasized the importance of mutual haptic interaction for skill learning in the presence of dual instability, would provide possible new insights into training in education, sport or rehabilitation. Also, the study would be of significance to study new joint action paradigms where the success depends on predicting partner's possible actions[3]. Apart from human-human interaction, this study would make contributions to promising studies on simulator training, robot therapists or medical training robotic systems.

Conclusion

Experimental results suggested that (1) sequential learning of interaction dynamics enhanced performance more than simultaneous learning. (2) In simultaneous learning the performance improvement depends on the quality of haptic interaction between the participants. However, in case of sequential learning it does not matter whether there is mutual interaction. (3) As a first dynamic, learning the internal model of environmental dynamics induced better performance improvement than partner dynamics. In motor learning, it is important to form internal models for adaptation to interaction dynamics. Therefore, the findings will be useful to further investigate human-human interaction, and also design human-robot interface including robot therapists.

Methods

Participants

Thirty-five subjects (25 female and 10 male, average age 29.1±3.15 years) participated in the study and provided written informed consent. Four female subjects were left-handed, and the rest were right-handed according to the Edinburgh Handedness Inventory[33]. All used their dominant hand for this study. This study was approved by the ethical committee of the University of Reading, and the experimental methods were performed in accordance with the relevant guidelines and regulations.

Experimental Setup and Task

In the study, the participants were asked to move a joint cursor (a 10 kg mass, visualized as a red circle with 5 cm radius) from a home position ($[x_0,y_0]$=[0,0]) to randomly placed target (visualized as a yellow circle with 5 cm radius) as quickly as possible by controlling the haptic arm (shown in Fig.1) with their partner or alone. The target appeared randomly at one of eight locations equally spaced at 45 degree on a circle with radius 60 cm around the home position of the joint cursor in each trial. A trial has been completed successfully when the joint cursor crossed into the target. During the trial, the position of the cursors (blue and purple circles) controlled by the paired participants and virtual springs (blue and purple springs) were invisible. Thus, the participants interacted with their partner through solely haptic feedback such that one was pulled towards the cursor position of the other participant sitting in the separate room. After each successful trial, the target disappeared and the blue and purple cursors were visible on the display. The participants were asked to move their own cursor to their own cursor's home position on the computer screen to begin the next trial. The home position was set as[-50,0] for *Cursor 1* and [50,0] for *Cursor 2*.

'Haptic feedback' was provided by using two Phantom-like haptic devices with two degrees of freedom (DoF), which control the cursor positions on the xy plane. As set up in our previous study[12], each haptic device was equipped with two encoders (HEDM-5500 Incremental Encoder with resolution 1000 cycles per revolution) to measure the position of the cursor in the virtual environment and two DC Motors (RE25 Maxon) to generate forces through virtual springs. Realtime control of the system was implemented with UDP Ethernet connection between Host PC and xPC Target by using MATLAB Simulink software package (the Mathworks Inc., MA, USA).

As shown in Fig.1, the joint cursor was connected to the end-effectors of the haptic arms via nonlinear virtual springs generating two force vectors ($\vec{F}_{c1}$ and $\vec{F}_{c2}$). The magnitude of force on the virtual springs (F_{c1} and F_{c2}) was calculated using the following equations:

$$F_{c1} = k_1 L_1 + k_2 L_1^2 \tag{1}$$

$$F_{c2} = k_1 L_2 + k_2 L_2^2 \tag{2}$$

L_1 and L_2 indicate the lengths of the virtual springs between the virtual mass and cursors controlled by participants (cursor 1 and cursor 2 respectively). In the present study, the stiffness factors of these virtual springs (k_1 and k_2) were determined same as in our previous study[12] (k_1 = 148 and k_2 = 1480).

$$M\frac{d^2\vec{p}_m}{dt^2} + B\frac{d\vec{p}_m}{dt} = F_{c1} + F_{c2} \tag{3}$$

$\vec{F}_{c1}$ and $\vec{F}_{c2}$ were used to drive a mass (M)/damper (B) system (in 2 DoF).

In this study, we focused on 'dual instability' (i.e. instability based on two unknown dynamics; environmental or partner dynamics; Fig.1). To simulate environmental dynamics in the virtual environment, an external force field ($\vec{F}_{ext}$) was applied to the virtual mass by considering the stiffness factor (k_{ext}) as 596.

$$\vec{F}_{ext} = k_{ext} \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} x_m - x_0 \\ y_m - y_0 \end{bmatrix} \tag{4}$$

When the external force field was applied, the equation used to drive a mass (M)/damper (B) system was revised using the following equation:

$$M \frac{d^2 \vec{p}_m}{dt^2} + B \frac{d \vec{p}_m}{dt} = F_{ext} + F_{c1} + F_{c2} \tag{5}$$

Experimental Conditions

To investigate 'how the order (sequential or simultaneous) of dual instability (e.g. environmental or/and partner dynamics) affect skill learning process', the experiment was performed in 4 conditions (Table 2). 35 participants were randomly assigned to one of these conditions. Each condition consists of three main experimental sessions: Familiarization (FS), Training (TS) and Wash out (WS). Each session consists of a number of target-set including 8 trials. Whereas FS and WS were performed in the same manner, the Training sessions differed in each condition (e.g. Training *without* External Force, Training *with* External Force, Single Training or Paired Training). There was no external force field in the FS and WS in each condition.

- Condition 1 (cooperative sequential learning): 'Is it possible to learn environmental dynamics with an interacting partner after familiarisation with the partner's dynamics?' The experiment was divided into 4 sessions with 10-minute break: Familiarization, Training *without* External Force, Training *with* External Force and Wash out. In the Training session, participants first familiarized with their partners, and then performed the task with their interacting partner under the external force field.

- Condition 2 (simultaneous learning): 'Is it possible to learn environmental dynamics and partner's dynamics simultaneously?' The experiment was divided into 4 sessions with 10-minute break: Familiarization, Training *with* External Force, Training *without* External Force and Wash out. In the Training session, participants were first exposed to unknown partner dynamics under the external force field, and then the external force field was removed from the task.

  In each of Condition 1 and Condition 2, ten participants were recruited in pairs to form five dyads, and each session was performed with an interacting partner.

- Condition 3 (individual sequential learning): Is it possible to learn partner's dynamics under environmental dynamics after familiarisation with the environmental dynamics individually? The experiment was divided into 4 sessions with 5-minute break: Familiarization, Single Training *with* External Force, Paired Training *with* External Force and Wash out. In the Training session, participants firstly performed the task under the external force field as a single to familiarize with the environmental dynamics. Then, the same task was performed under the external force field with an unknown partner. The condition was performed by 5 pairs (10 participants). The first Training session (the session before the break) was performed as a single and the second one was performed as a pair.

- Condition 4 (individual learning): Is it possible to learn environmental dynamics without a partner? The experiment was divided into 3 sessions: Familiarization, Training *with* External Force and Wash out. Each session was performed individually. In Training session, the external force field was applied to the task. The condition was performed by 5 participants.

  Our hypothesis was that separation of unknown dynamics would result in skill learning. Thus, the primary study was the comparison of Condition 1 (cooperative sequential learning) and Condition 2 (simultaneous learning). Condition 3 (individual sequential learning) was performed to investigate the effect of the order of unknown dynamics in skill learning process. Condition 4 (individual learning) was set as a check-mark to ensure that no factors are inadvertently overlooked. In the light of the previous studies[7,34], in which the Training session consists of approximately 240 trials (30 TS), first, we selected the number of target set of the Training session in Condition 1 and Condition 2 as 320 trials (40 TS) to evaluate the motor performance. Skills are acquired by training. As shown in Fig. 6, the learning curve initially shows a steep decrease in time to target (i.e. a steep increase in performance improvement) over a period of practice, and after a variable number of training sets (nearly 15 TS) performance typically plateaus. Thus, the number of target sets were reduced in Condition 3 and Condition 4.

  The time to complete whole experiment for Condition 1 and Condition 2 was approximately 2-hours whereas for Condition 3 and Condition 4 it was 1 hour.

Data Analysis

All data analyses were performed in Matlab version R2017b. 2-D Cartesian coordinates (x-y plane) of the cursors controlled by participants and joint cursor were recorded at 1 kHz and used to calculate other kinematic variables (velocity). In this study, we did not analyze the return movements to the home position.

First, we quantified Familiarization and Wash Out session (before and after the Training session) to evaluate the performance improvement in each condition. Next, we analyzed Training session to investigate the principle behind skill learning. Therefore, we computed the following indicators:

Time to Target: The duration of a successful trial which refers to the time to move the joint cursor to the target. The time to target is expected to reduce with skill learning (Fig.6).

Trajectory: The other feature to analyze the point-to-point trajectories is trajectory smoothness[26]. Trajectory smoothness is expected to increase with skill learning[35]. In this study, trajectory smoothness was measured with the sum of trajectory curvature and the number of peaks in velocity (Fig.3).

The cursor positions ($\vec{p_{c1}}$ and $\vec{p_{c2}}$) were recorded in 2D Cartesian coordinates (x-y plane). The trajectory curvature (c)[26] was calculated using the following equation:

$$c = \frac{(\dot{x}\ddot{y} - \dot{y}\ddot{x})}{(\dot{x}^2 + \dot{y}^2)^{3/2}} \tag{6}$$

where x represents the cursor position in x-coordinate and y represents the cursor position in y-coordinate. $\dot{x}$ and $\dot{y}$ are the differential of the time series of coordinate position data (x and y, respectively), and $\ddot{x}$ and $\ddot{y}$ are the corresponding accelerations. Additionally, changes in sub-movements also characterize the process of skill learning[29,36], such that an increase in the number of sub-movements or the interval between two successive sub-movements leads to decrease in trajectory smoothness, which resulting in decrease in skill learning. In this study, sub-movements were extracted from participants' tangential velocity data[29]. Velocity was calculated as the differential of the time series of coordinate position data.

Force: Force applied to move the joint cursor to the target in x and y direction. As shown in Fig.5, the net force was described by a sum of vector norms of the force applied by each participant ($\vec{F}_{net} = \vec{F}_{c1} + \vec{F}_{c2}$). The average of the contribution of each member in each pair during the Training session (see Table 1) was calculated by dividing the applied force by each member into the total force applied by a pair.

The expected force ($\vec{F}_{exp}$) was determined as the desired force to move the virtual mass to the target in a straight way. In addition, to evaluate the motion accuracy, the angle (α) between the net force ($\vec{F}_{net}$) and the expected force ($\vec{F}_{exp}$) was calculated using the following equation:

$$\alpha = \cos^{-1}[(F_{net}.F_{exp})/\left|F_{net}\right|\left|F_{exp}\right|] \tag{7}$$

It is important to note that when paired participants apply a force at the same time to interact with their partner and environment, a haptic channel is created. Based on previous study[30], we quantified the following outcome measure:

Haptic State: A combination of binary force to identify the haptic interaction between paired participants. To determine the haptic states[30], first, the force data was filtered using a low pass filter function in MATLAB with a cut off frequency of 25 Hz. The first 250-millisecond of each trial was discarded to remove the noise caused by starting to manipulate the end-effector of the haptic device. The filtered force data was normalized with z-score for each trial by subtracting the average force from individual force and then dividing by the standard deviation. Within each 250-ms time window, a threshold (F_{thr}) was determined as 10 % of the maximum value of the normalized forces and compared with the average value. The binarized force (F_b) was determined by comparing the threshold (F_{thr}) and the average value (F_{avr}) as shown in the following equation:

$$if \begin{cases} F_{avr} < F_{thr}, & F_b = 0 \\ F_{avr} > F_{thr}, & F_b = 1 \end{cases} \tag{8}$$

Then, the haptic states were identified by combining the binarized forces:

- if $F_{b1} = 0$ and $F_{b2} = 0$, Haptic State = 1
- if $F_{b1} = 0$ and $F_{b2} = 1$, Haptic State = 2
- if $F_{b1} = 1$ and $F_{b2} = 0$, Haptic State = 3
- if $F_{b1} = 1$ and $F_{b2} = 1$, Haptic State = 4

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Author contributions statement

TK and YH conceptualized the research project. OS did participant experiments, analyzed the data set, and discussed the results with WH, TK, and YH. All authors contributed to writing a draft of the paper and read and approved the final manuscript.

Data Availability Statement

The data analyzed in the current study are available from the corresponding author on reasonable request.

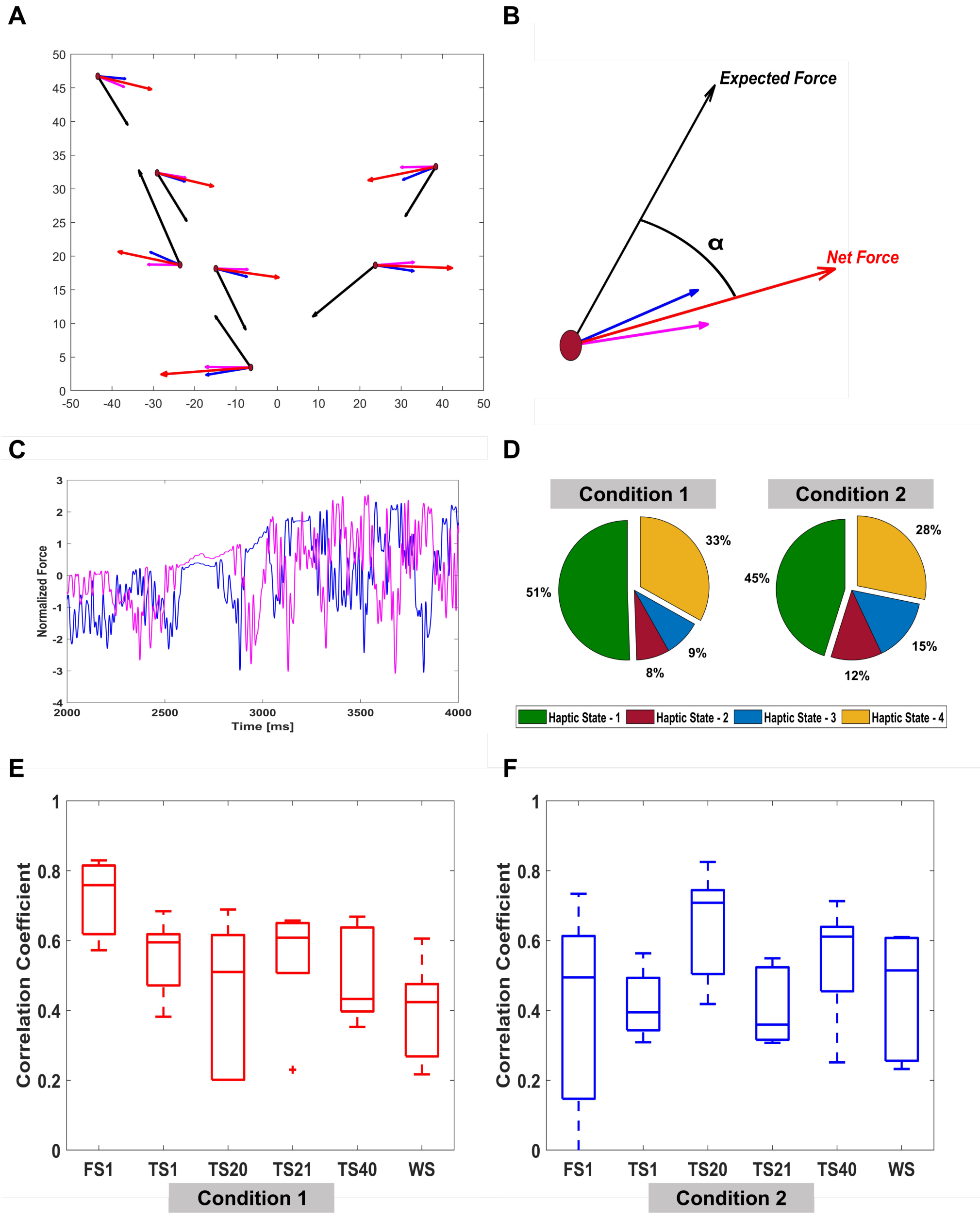

Figure 5. Force analysis. **(A)** A typical example of force analysis in sub-movements. **(B)** The force profile. Blue and purple indicate the force applied on Cursor 1 and Cursor 2, respectively, to move the joint cursor to the target. The red vector shows the net force on the joint cursor and the black vector shows the expected force. The angle between the net force and the expected force was characterized by calculating α. **(C)** The force as a function of time. Blue and purple represent the force recorded from participant A and B and normalized using z-score. **(D)** The percentage of 4 Haptic States in the whole experiment. Haptic State 1: none of participant A and B applied force above threshold. Haptic State 2 and 3: one of the participant A or B applied force above threshold. Haptic State 4: paired participants apply force above threshold at the same time. **(E),(F)** The correlation coefficient between force A and B. Time points: FS1 (first set of Familiarization session), TS1 (first set of first Training session), TS20 (last set of first Training session), TS21 (first set of second Training session), TS40 (last set of second Training session) and WS (Wash Out session).

Table 2. Experimental Conditions

Condition 1 (n=10)

Familiarization (2 FS)	Training ***without*** External Force (20 TS)	Break (10-min)	Training ***with*** External Force (20 TS)	Wash out (1 WS)
P_1-P_2	P_1-P_2		P_1-P_2	P_1-P_2
P_3-P_4	P_3-P_4		P_3-P_4	P_3-P_4
...	...		...	...

Condition 2 (n=10)

Familiarization (2 FS)	Training ***with*** External Force (20 TS)	Break (10-min)	Training ***without*** External Force (20 TS)	Wash out (1 WS)
P_{11}-P_{12}	P_{11}-P_{12}		P_{11}-P_{12}	P_{11}-P_{12}
P_{13}-P_{14}	P_{13}-P_{14}		P_{13}-P_{14}	P_{13}-P_{14}
...	...		...	...

Condition 3 (n=10)

Familiarization (2 FS)	Training ***with*** External Force (3 TS)	Break (5-min)	Training ***with*** External Force (14 TS)	Wash out (1 WS)
P_{21} | P_{22}	P_{21} | P_{22}		P_{21}-P_{22}	P_{21} | P_{22}
P_{23} | P_{24}	P_{23} | P_{24}		P_{23}-P_{24}	P_{23} | P_{24}
...	...		...	...

Condition 4 (n=5)

Familiarization (2 FS)	Training ***with*** External Force (14 TS)	Wash out (1 WS)
P_{31}	P_{31}	P_{31}
P_{32}	P_{32}	P_{32}
...	...	...

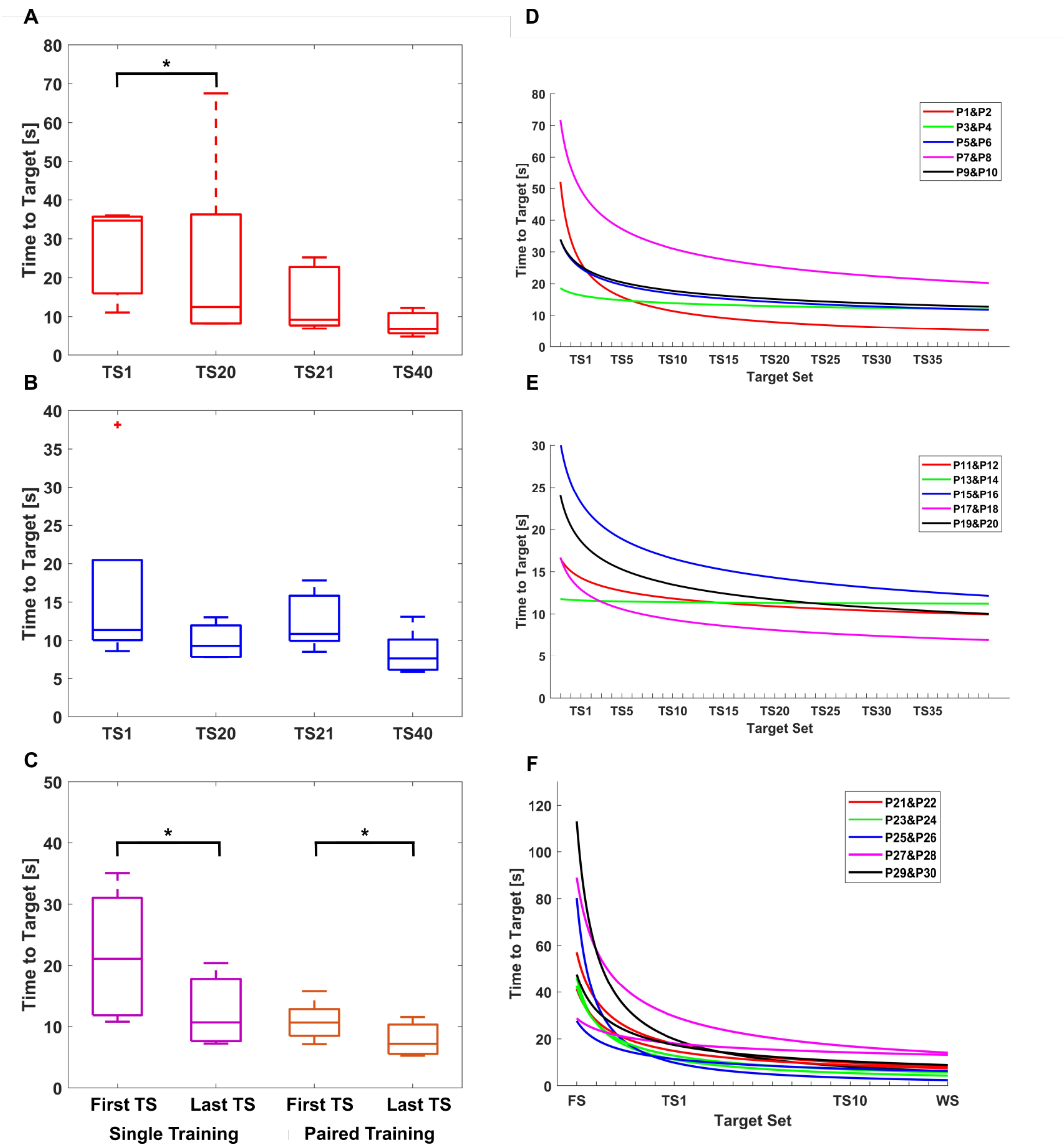

Figure 6. Learning Curve obtained with the power law. Asterisks denote significant differences ($p < 0.05$) according to a paired t-test. Panel **(A)**, **(B)** and **(C)** represents the learning curve based on the average time to target of all participants in the Training session of Condition 1, Condition 2 and Condition 3, respectively. Panel **(D)**, **(E)** and **(F)** represents the learning curve of each participant separately in Condition 1, Condition 2 and Condition 3, respectively. The large amount of performance improvement occurred during early practice (FS), and the rate of performance improvement decreased in other sessions (TS and WS).

Chapter 6

Sequential Learning via Haptic Interaction: A Pilot Hyperscanning Study

Chapter 3, chapter 4 and chapter 5 showed that mutual skill learning can happen only when there is adaptability through mutual active interaction. However, there is still uncertainty as to how the electrical brain activity changes in case of mutual motor learning. Hyperscanning, which means simultaneous recording of neural signals of two or more people, may be able to find the electrical brain activity changes induced by mutual motor learning. This chapter aims to investigate the neural signatures of mutual motor learning by recording dual-EEG activity of dyads while performing a motor task via haptic interaction. As in chapter 5, a haptic robotic interface plays an important role as being the channel for mutual sharing of intentions in this study (see Methods section or Appendix A for details). This is a pilot study with promising findings, but its limitations must be taken into consideration.

6.1 Introduction

Recent studies on skill learning [11, 31] raised the issue of dual instability. While performing a cooperative task through the interaction with others, people can face dual instabilities arising from the environment (i.e. unknown environment with external force field) and interaction with a partner (i.e. the person performing the task together). The studies presented in Chapter 3, Chapter 4 and Chapter 5 showed that mutual skill learning can happen only in the presence of adaptability. Also, sequential learning (i.e. learning dual dynamics in a sequence) resulted in mutual skill learning (i.e. skill learning through the interaction with a person who have same skill level). However, there is still uncertainty as to how the electrical brain activity changes in case of mutual motor learning.

It is known that mutual behavioural negotiation or mutual adaptation results in inter-brain synchrony (i.e. synchrony between two brains) [20]. In this study, we hypothesize that mutual motor learning which is a result of mutual adaptation would lead to inter-brain synchronization. For a successful motor performance inter-brain synchronization means that there should be a neuronal marker for social behaviour, going beyond the superficial synchronisation of body parts.

In previous studies, behavioural synchrony resulted in an increase in phase synchronization in the alpha-mu frequency band [1,20]. Additionally, specific frequencies in the alpha-mu frequency band including Phi1 and Phi2 were defined as neuromarkers of social cooperation.

Our aim is to identify the neuronal markers for successful mutual learning within a brain and inter-brain. EEG-hyperscanning, which means Electroencephalography (EEG) recording of neural signals from two or more people simultaneously, may be able to find the changes in brain dynamics induced by mutual motor learning. Previous EEG-hyperscanning studies [1, 79, 97] showed that in a finger-tapping task synchrony between participants' fingertip movements and inter-brain synchrony increased with the cooperative training. It is known that synchronous neural oscillations can reveal much about cognitive processes [113]. Inter-brain synchrony is a signature of implicit interpersonal interaction, and also increased synchrony is correlated to increased communication between participants [114].

To our knowledge, this is the first study to record dual-EEG activity of dyads while performing a motor task in haptic interaction. We implemented an EEG-hyperscanning environment to find the neuromarkers of dyadic haptic interaction and mutual skill learning. To solve the issue of dual instability, a person must distinguish sensory changes arising from their own motion, partner's motion or environmental dynamics subject to external force field. The central nervous system (CNS) allows for discrimination of one's own motion and other dynamics including partner and environmental dynamics [27, 102]. A successful mutual motor performance relying on development of the internal model would play a key role in anticipating the motion of each other.

In this study we will investigate the neural changes within each participant's brain (intra-brain) and between members of each pair (inter-brain) while performing a cooperative motor task using a haptic robotic interface (as shown in Fig.6.1). In cooperative tasks, people need to predict their partner's motion to control their own motion. The haptic robotic interface plays an important role as being the channel for mutual sharing of intentions.

6.2 Methods

6.2.1 Subjects

Four volunteers (3 male and 1 female, between the ages of 25 and 40) with no prior experience took part in the pilot study. The participants were grouped randomly in the beginning of the experiments. Note that spectral EEG frequency power changes with age such that alpha power increases, and theta power decreases with aging [113]. All the participants were all right-handed according to the Edinburgh Handedness Inventory [115], and reported no history of neurological disease. Each participant provided written informed consent. This study was approved by the ethical committee of the University of Reading, and the experimental methods were performed in accordance with the relevant guidelines and regulations.

6.2.2 Experimental Setup

The experiment was performed using the same haptic-motor task described in Chapter 5. As shown in Fig.6.1, in the experiment, the participants were seated in a comfortable chair in front of a computer screen and held the robotic haptic arm with their right hand. We asked participants to control a cursor (representing the position of robotic arm) to bring a joint-cursor to a randomly placed target with their preassigned partner who sat in a separate room. During a trial, the position of the joint-cursor and target were represented on the virtual environment. The target appeared at one of eight locations equally spaced at 45 degree on a circle around the home position of the joint cursor in each trial. However, there was no visual information related to one's own or partner's cursor position on the screen. The paired participants interacted with each other through pure haptic feedback such that one was pulled towards the other participant sitting in the separate room. Two Phantom-like haptic devices with two degrees of freedom (DoF) were used to provide haptic feedback. The experimental paradigm was developed in MATLAB Simulink R2015b.

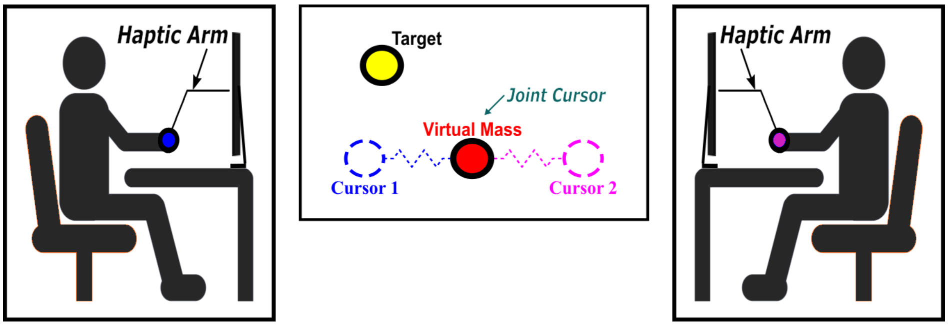

Figure 6.1: Experimental task; a virtual mass (joint cursor; red circle) was connected to two cursors (blue and purple circle) with virtual springs and subject to external force field. The paired participants who sit in separate identical rooms were asked to move the joint cursor to the target (yellow circle) by manipulating their own haptic arm. Each cursor on display indicates the end-effector of each haptic arm. During a trial, there was no visual information related to virtual springs and cursor positions. The participants interacted with each other through pure haptic feedback. After each successful trial, participants were asked to move their own cursor onto the home position.

To identify the neural correlates, each participant was fitted with a 32-electrode EEG cap (g.GAMMA cap, g.tec medical engineering GmbH Austria, shown in Fig.6.2). Using dry electrodes might lead to worse results [95], so a conductance gel was applied between each wet electrode and scalp to ensure reliable EEG recording, As shown in Fig.6.3, the EEG channels were positioned at Fp1, Fp2, F7, F3, Fz, F4, F8, FT9, FC5, FC1, FC2, FC6, FT10, T7, C3, Cz, C4, T8, TP9, CP5, CP1, CP2, CP6, TP10, P7, P3, Pz, P4, P8, O1, Oz and O2 following the international 10-20 system [116]. The numbers 10 and 20 indicate the distance between adjacent electrodes [83]. The reference electrode was placed on the right ear, and the ground electrode was placed at the position of AFz. Cz represents the central midpoint between nasion and inion. The impedances were kept below 10kΩ [117].

A detailed description related to the set up can be found in appendix A.

Figure 6.2: 32-electrode EEG cap (g.GAMMA cap, g.tec medical engineering GmbH Austria)

6.2.3 Experimental Protocol

As shown in Table 6.1, the experimental protocol was set as in 4 phases with 5-minute break; baseline, training without external force field, training with external force field and evaluation, respectively. Each experimental phase consists of a number of training-set (TS), each including 8 trials. After each training-set, the participants were given a 5-second break. First, baseline phase including 2 TS was performed to be familiar with the experimental task. In the next two-phase, participants were trained with the task: in order; (1) without external force field to be familiarized with their partners (2) with external force field to assess skill learning with a familiarized partner under the external force field. Between these two training phases, participants were given a 5-minute break to rest. Lastly, evaluation phase including 1 TS was performed to test the hypothesis.

Table 6.1: Experimental Protocol

Baseline (2 TS)	Training **without** External Force (6 TS)	Break (5-min)	Training **with** External Force (6 TS)	Evaluation (1 TS)
P_1-P_2	P_1-P_2		P_1-P_2	P_1-P_2
P_3-P_4	P_3-P_4		P_3-P_4	P_3-P_4
...	...		...	...

Each experiment lasted for about 1 hour and 20 minutes, including the time to prepare each participant for EEG set-up (10-min) and remove them (10-min).

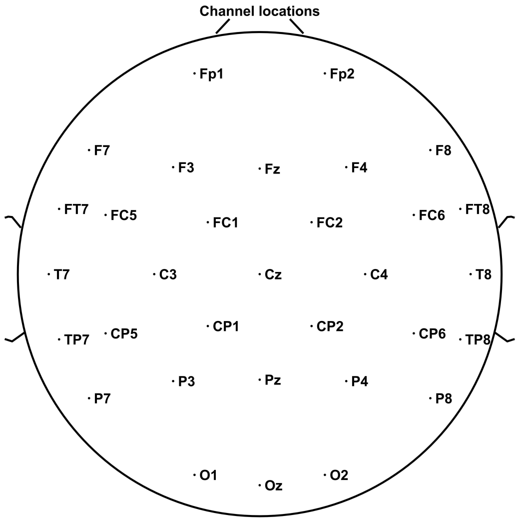

Figure 6.3: Electrode placement according to the international 10-20 system [83,116] (plotted in EEGLAB); Fronto-parietal (Fp1, Fp2), Frontal (F7, F3, Fz, F4, F8), fronto-central (FC5, FC1, FC2, FC6), fronto-temporal (FT7, FT8), temporal (T7, T8), central (C3, Cz, C4), centro-parietal (CP5, CP1, CP2, CP6), parietal (P7, P3, Pz, P4, P8), tempo-parietal (TP7, TP8), occipital (O1, Oz, O2); even numbers for the right hemisphere, and odd numbers for the left hemisphere. z points are on the midline.

6.2.4 Behavioural Data Analysis

To assess skill learning, the following parameters were recorded:

1) Time point when both two participants place their own cursor on the home position

2) Time point when holding the joint-cursor on the target

3) 2D coordinates of the movements followed by each participant

4) 2D coordinates of joint-cursor

Behavioural data was recorded at 1 kHz and data analyses were performed in MATLAB R2019b. First, we calculated time to bring the joint cursor to the target in each training-set of each phase. Baseline and Evaluation phase (before and after the Training phase) were evaluated to assess the performance improvement due to motor learning during the Training phase. Next, trajectory analysis was performed by evaluating movements followed by paired participants, which also allowed for assessment of behavioural synchrony in movements.

6.2.5 EEG Data Analysis

EEG data analyses were done offline using MATLAB R2019b and EEGLAB 2021. Each experimental trial was recorded with the sampling frequency of 1000 Hz to obtain sufficient EEG data with high temporal resolution. Before recording, a low-pass filter with 100 Hz cutoff, a high pass filter with 0.5 Hz cutoff and a notch filter at 60 Hz were set on the amplifier using a set of DIP switches.

EEG signals are vulnerable to various artifacts due to having small amplitude [118]. Thus, the first step in EEG analysis was filtering to remove extrinsic and intrinsic artifacts [95, 96, 119, 120]. To remove extrinsic artefacts caused by physical or environmental factors, EEG signals were filtered using a fourth order Butterworth Filter with a 60 Hz cut-off frequency and a Notch Filter at 50 Hz. The filtered EEG signals were visually inspected to remove large spikes with more than 100 mV. Since independent components analysis (ICA) was found more efficient than principal components analysis (PCA) [95], ICA [121] was applied to remove intrinsic artifacts arising due to eye blinking, vertical eye movement or muscular movement. The artifacts were identified using a function named 'runica()' for automated infomax ICA decomposition [122] in EEGLAB toolbox of MATLAB (sccn.ucsd.edu/eeglab/) [123]. Eye movement artifacts were found in the frontal lobe, specifically mid-frontal region as expected [83]. The EEG signals with at least 90 $\%$ noise were removed from the data offline. Within the experiment, the reaction time (i.e. the time between the starting time and the initiation of the movement) was measured as 200 ms, so the first 200 ms of EEG recording was removed before the analysis.

For the analysis, EEG signals were down-sampled to 250 Hz and band-pass filtered to one of main five frequency bands including delta (1-3 Hz), theta (4-7 Hz), alpha (8-13 Hz), beta (14-29 Hz), and gamma (30-40 Hz). Also, there is mu rhythm within the frequency range between 8 and 12 Hz over the sensorimotor cortex, overlapping with alpha rhythm. A previous study highlighted that the frequency range from 4 to 20 Hz is involved in interpersonal interaction [70]. Another study [1], also, stated that phi-1 (10-12 Hz) decreased, and phi-2 (12-12.5 Hz) increased during coordinated movement. Thus, EEG signals were, also, band-pass filtered to these two frequency ranges to identify neural correlates associated with social interactions. The filtered EEG data was analysed using a sliding window of 500 milliseconds.

First, Time-Frequency analysis was performed on each training-set of each phase to extract information from the EEG signals in the time domain. The mean absolute power of the EEG was calculated by Fast Fourier Transformation (FFT) in the specified frequency bands: delta (1-3 Hz), theta (4-7 Hz), alpha (8-13 Hz), beta

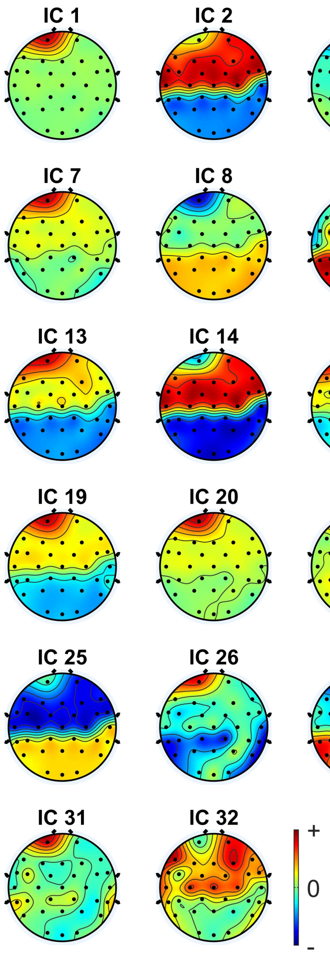

Figure 6.4: Topographical 2D scalp maps of the independent components (ICs) obtained using Independent Components Analysis (ICA) in EEGLAB toolbox

(14-29 Hz), gamma (30-40 Hz), phi-1 (10-12 Hz) and phi-2 (12-12.5 Hz). Next, to understand the neural changes underlying synchronization, Event-Related Potential (ERP) analysis was performed using EEGLAB [123]. In ERP analysis, the filtered EEG signals were averaged in the selected time epoch, which was the response time to sensory stimuli [124, 125]. Previous studies showed that motor learning led to changes in the EEG signals in form of an Event-Related (de) Synchronization (ERD/S) [126]. Event-Related Desynchronization (ERD, decrease in power) indicates the decrease in synchrony between two neuronal elements whereas Event Related Synchronization (ERS, increase in power) shows the coherent activity [127]. ERD/S is used to quantify the changes in EEG power within the specified frequency band with high temporal resolution [83]. Thus, ERD/S, the relative change in the bandpower, was computed using Eq. (6.1).

$$ERD = (\frac{A - B}{B}) \times 100 \tag{6.1}$$

where B is the baseline band power obtained from the mean of EEG signals between the starting time and the initiation of the movement, and A is the mean band power of each 500-ms sliding window in each training-set.

Previous research [128] showed that circular correlation (CCorr) is more robust to measure phase synchronization between two EEG time series than phase locking value (PLV), partial directed coherence (PDC) or Kraskov mutual information (KMI), since CCorr is insensitive to changes in variance and unbiased to detect coupling. Thus, in this study, circular correlation was calculated to investigate inter-brain phase synchronization between paired participants. The circular correlation [128] was computed on each training-set using Eq. (6.2) .

$$CCorr_{\varphi,\rho} = \frac{\sum_{k=1}^{N} sin(\varphi - \bar{\varphi}) sin(\rho - \bar{\rho})}{\sqrt{\sum_{k=1}^{N} sin^2(\varphi - \bar{\varphi}) sin^2(\rho - \bar{\rho})}} \tag{6.2}$$

where φ and ρ indicate the amplitudes of EEG channel 1 and channel 2 signals, extracted using the Fast Fourier Transformation (FFT) from delta, theta, alpha, beta, gamma, phi-1 and phi-2 frequency band passed signals, and shifted by 100 ms. $\bar{\varphi}$ and $\bar{\rho}$ indicate the mean amplitude of the corresponding channel. The circular correlation ranges between -1 and 1. If the correlation is zero, there is no correlation between the specified EEG channels. If the correlation is -1, the EEG channels are negatively correlated. If the correlation is 1, the EEG channels have a positive correlation [128].

6.2.6 Regions of Interest

Previous studies showed that neural changes related to feedback processing and performance monitoring were observed in medial prefrontal cortex (mPFC) [13,101]. The activation of medial prefrontal cortex located in the frontal lobe has been shown in theta band (4-8 Hz) [101,103,108]. Also, in a motor task, practice resulted in higher theta synchronization in the frontal region [108]. Thus, theta activity was observed in the mid-frontal lobe (Fz, as defined by the 10/20 system) to evaluate the performance of each pair within the motor task. Additionally, alpha and beta activity were observed in primary motor cortex (including C3, Cz and C4 electrode in the 10-20 system) while learning motor skills [26]. The power of beta band decreased in the central lobe after executing the motor task. EEG-hyperscanning studies [1, 20] highlighted the importance of the right centro-parietal region (channel C4, CP2, P4 and CP6) in movement synchronization. The alpha–mu band and phi complex including phi-1 and phi-2 were observed while performing synchronic behaviours such as executing joint tasks [1, 55]. Following the studies, the alpha, phi-1 and phi-2 were computed in the right centro-parietal region to evaluate social interaction.

6.3 Results and Discussion

As shown in Table.6.1, the participant experiments consist of four phases in which training phase was performed in two different forms: First, the external force field was omitted in Training without External Force phase to allow participants to be familiar with partner dynamics. Second, in the Training with External Force phase, the external force field was applied in the virtual environment to assess learning the environmental dynamics through the interaction with the partner, which would result in sequential learning of dual dynamics (i.e. partner and environmental dynamics).

The pilot study was performed with four participants (two-pairs) to explore behavioural and neural correlates of sequential learning. When comparing Baseline (before Training) and Evaluation (after Training) phase, Pair 2 showed a decrease in the average time to target; a decrease from 29.7 to 12.1 seconds (Fig.6.5). On the contrary, Pair 1 showed an increase in the average time to target; an increase from 5.25 to 10.5 seconds (Fig.6.5). The decrease in time to target indicates the learning of dual dynamics (i.e. partner and environmental dynamics). When analysing Training phases independently, the average time increased in both pairs in the first Training phase although the external force was omitted. On the other hand, within the second Training phase (i.e. with external force field), the average time decreased from 6.2 to 5.2 seconds in Pair 2, however, increased from 3.8 to 6.2 seconds in Pair 1 (Fig.6.5).

Next, trajectories were analysed to investigate the differences in the Training phases. Typical trajectories followed in each Training phase were shown in Fig.6.6 (no external force) and Fig.6.7 (with external force). When comparing the joint-cursor trajectories (red line connecting red circle to the green one in Fig.6.6A and Fig.6.7A), the trajectory is much more complicated under the external force (Fig.6.7A) than the absence of the external force (Fig.6.6A). When dividing the movement of joint-cursor (Fig.6.6A) into sub-movements (Fig.6.6B and Fig.6.6C), first, the paired participants moved their own cursors to the opposite direction (i.e. anti-phase synchronization [5], Fig.6.6B), and then followed the same direction (i.e. in-phase synchronization [5], Fig.6.6C). The in-phase and anti-phase synchronization was seen,

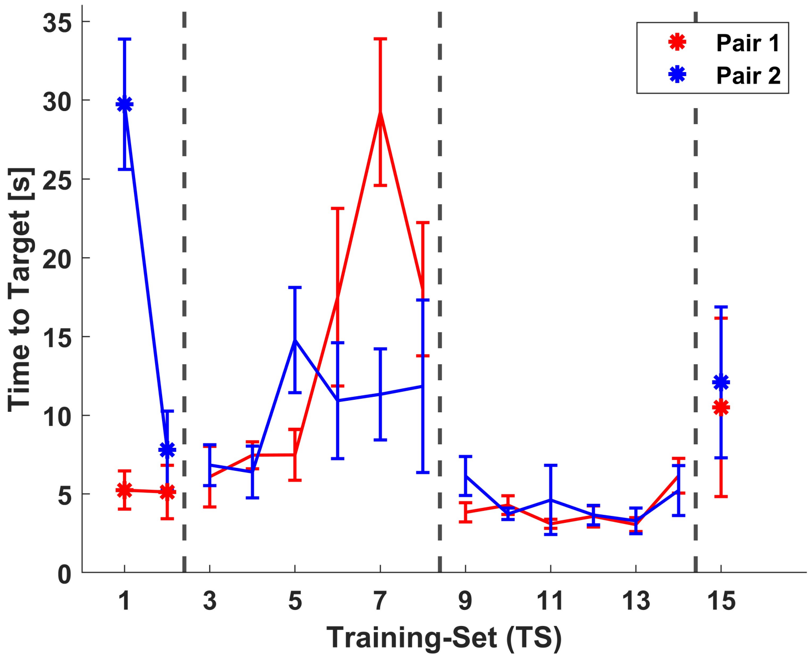

Figure 6.5: Average time to bring the joint cursor to the target in each training set (with standard error). The experiment consists of 4 experimental phases with 15 training-set in total: Baseline phase (2TS), Training without External Force phase (6TS), Training with External Force phase (6TS) and Evaluation (1TS), respectively.

also, in the movements under the external force field (shown in Fig.6.7).

The study aimed to identify neural correlates of sequential learning (i.e. learning partner and environmental dynamics sequentially). To this aim, first, we analyzed the EEG data within the time period including in-phase and anti-phase synchronization. Spectral characteristics of EEG signals were determined with seven frequency bands ranging from 1 to 40 Hz respectively delta (1-3 Hz), theta (4-7 Hz), alpha (8-13 Hz), beta (14-29 Hz), gamma (30-40 Hz), phi-1 (10-12 Hz) and phi-2 (12-12.5 Hz). Previous research [108] suggested mid-frontal theta as a neuromarker of motor learning such that highly skilled athletes showed much more distinct theta activity than the novice one in the frontal area. Thus, we have chosen mid-frontal electrode (Fz) to explore the neural correlates of in-phase and anti-phase synchronization. During the anti-phase synchronization, the amplitude in Fz decreased in one subject, on the contrary, increased in the other one (Fig.6.6D). When analysing Event-Related Potential (ERP) signal changes at Fz, the ERPs showed a decrease in Subject 1 in case of an increase in Subject 2 (Fig.6.8). On the other hand, during in-phase synchronization, the amplitude in Fz increased or decreased in both subject at the same time (Fig.6.6E).

Recent study [1] identifed Phi1 and Phi2 as a neuromarker of social coordination, such that Phi1 increased with independent behaviour, and Phi2 increased with coordinated behaviour. We hypothesized that a decrease in Phi2, resulting decrease in coordinated behaviour would be an obstacle to skill learning with a partner. To investigate the reason of the performance decrease in Pair 1, the mean Phi1 and Phi2 amplitude were computed over the centro-parietal region (CP5, CP1, CP2 and CP6) for each subject in each training-set by averaging the EEG signals in 8 trials.

The mean of Phi1 at CP2 increased in each subject of Pair 1 during Training phase, whereas it increased in one subject of Pair 2, and decreased in other (Table 6.2). Meanwhile, there was no clear result when comparing the Phi1 at CP6. When comparing the Phi1 between the Training phases within a pair, the mean of Phi1 increased in each pair; from 11.22$\pm$0.67 to 11.35$\pm$0.37 in Pair 1, and from 11.15$\pm$0.28 to 11.22$\pm$0.26 in Pair 2 (Fig.6.9). There is a significant increase in Pair 2 ($p=0.036 < 0.05$), not in Pair 1 ($p=0.278$).

Table 6.2: The mean frequency of Phi1 band passed signals (in Hz) over Centro-Parietal region (CP5, CP1, CP2 and CP6) in the first training-set of each Training phase; the values in CP2 and CP6 are shown in bold to emphasize the change over right Centro-Parietal region.

Pair 1									
Subject 1	CP5	CP1	**CP2**	**CP6**	**Subject 2**	CP5	CP1	**CP2**	**CP6**
Force OFF	11.26	11.22	**11.13**	**11.18**	Force OFF	11.51	11.41	**11.28**	**11.3**
Force ON	11.51	11.52	**11.58**	**11.58**	Force ON	11.55	11.51	**11.44**	**11.11**
Pair 2									
Subject 3	CP5	CP1	**CP2**	**CP6**	**Subject 4**	CP5	CP1	**CP2**	**CP6**
Force OFF	10.88	10.83	**10.81**	**10.83**	Force OFF	11.03	10.86	**11.11**	**10.98**
Force ON	11.04	10.99	**11.3**	**10.88**	Force ON	10.77	11.15	**10.92**	**10.75**

When comparing the mean of Phi2 at CP2 and CP6, we found a decrease in each subject of Pair 1, and an increase in each subject of Pair 2 (Table 6.3). When comparing Phi2 between the Training phases, we found a significant decrease in Pair 1 ($p=0.0416 < 0.05$). The mean of Phi2 decreased from 12.59$\pm$0.19 to 12.50$\pm$0.20 in Pair 1, and, increased from 12.52$\pm$0.13 to 12.54$\pm$0.16 in Pair 2 (Fig.6.10).

To conclude, Phi2 significantly decreased in Pair 1 (Fig.6.11), which refers to a decrease in coordinated behaviour. On the other side, Phi1 significantly increased in Pair 2 (Fig.6.11), which refers to an increase in independent behaviour. The results suggest that the decrease in coordinated behaviour meaning decrease in mutual interaction would obstruct skill learning. Even though the results seem promising and consistent with previous studies [1], this is a pilot study including only four

Table 6.3: The mean frequency of Phi2 band passed signals (in Hz) over Centro-Parietal region (CP5, CP1, CP2 and CP6) in the first training-set of each Training phase; the values in CP2 and CP6 are shown in bold to emphasize the change over right Centro-Parietal region.

Pair 1									
Subject 1	CP5	CP1	**CP2**	**CP6**	**Subject 2**	CP5	CP1	**CP2**	**CP6**
Force OFF	12.53	12.52	**12.61**	**12.62**	Force OFF	12.68	12.68	**12.61**	**12.52**
Force ON	12.58	12.57	**12.57**	**12.6**	Force ON	12.85	12.73	**12.32**	**12.45**
Pair 2									
Subject 3	CP5	CP1	**CP2**	**CP6**	**Subject 4**	CP5	CP1	**CP2**	**CP6**
Force OFF	12.39	12.23	**12.28**	**12.37**	Force OFF	12.67	12.53	**12.51**	**12.37**
Force ON	12.36	12.51	**12.48**	**12.48**	Force ON	12.32	12.82	**12.58**	**12.64**

participants. Therefore, much more experiment (at least with 10 participants) is needed to confirm our findings.

The local neural synchronization analysis by evaluating power changes within a specific frequency band cannot provide strong evidence to understand neural mechanisms of interpersonal interaction [77, 129]. Therefore, to measure inter-brain synchronization, we calculated circular correlation between two participants of a pair in each training-set of each phase. The findings showed that the correlation in the Central region decreased in the alpha frequency band in Pair 1 (Table 6.4), however, increased in Pair 2 (Table 6.5) between Baseline and Evaluation phases and, also, between Training phases.

Table 6.4: Pair 1-Mean inter-brain circular correlation in the alpha band

	C3	Cz	C4
Baseline	0.0109	0.0114	0.0126
Training without Force	0.0087	0.0071	0.0172
Training with Force	0.0043	0.0057	0.0026
Evaluation	0.0093	0.0102	0.0113

The distributions of circular correlations calculated from shifted time series are shown in Fig.6.12. When analysing the Training phases in Pair 1, the distributions in the alpha band (8-13 Hz) had a mean, μ, of 0.004 and -0.002, and the standard deviation, σ, of 0.015 and 0.005 when the external force off or on, respectively. The cut-off was calculated as $\mu + 3 * \sigma$, giving a cut-off of 0.049 and 0.013, respectively. The three standard deviations ensure that 100$\%$ of the distribution values are below the cut-off (Fig.6.12). Also, we found that the mean correlation was higher in the

Table 6.5: Pair 2-Mean inter-brain circular correlation in the alpha band

	C3	Cz	C4
Baseline	0.0071	0.0067	0.0059
Training without Force	0.0094	0.0128	0.0059
Training with Force	0.0163	0.0224	0.0188
Evaluation	0.0085	0.0092	0.0081

Central region in Pair 2 (0.0109) than Pair 1 (0.0093), indicating the skill learning in Pair 2.

Additionally, the study aims to find how the functional brain network is affected from the haptic interaction with a partner under the external force field. Previous research showed beta-ERD associated with tactile stimulation, in particular, in the 16-20-Hz frequency band, and the parietal lobe (Pz) had a significance in the tactile perception. When comparing the ERSPs in the Training phases, the beta power at Pz decreased much more in Pair 2 than Pair 1 between Training phases (Fig.6.13).

6.4 Conclusions

The EEG-hyperscanning study investigated the neuromarkers of mutual skill learning. Recently, Phi1 and Phi2 have been determined as a neuromarker of social coordination, such that Phi1 increased with independent behaviour, and Phi2 increased with coordinated behaviour. Our main finding was the significant decrease in the Phi2 frequency in the case of no learning. We suggested that the decrease in coordinated behaviour could be due to the decrease in mutual haptic interaction, which would obstruct skill learning. It is important to develop an internal model mutually to anticipate the each other's motion, and so perform more successful motor task.

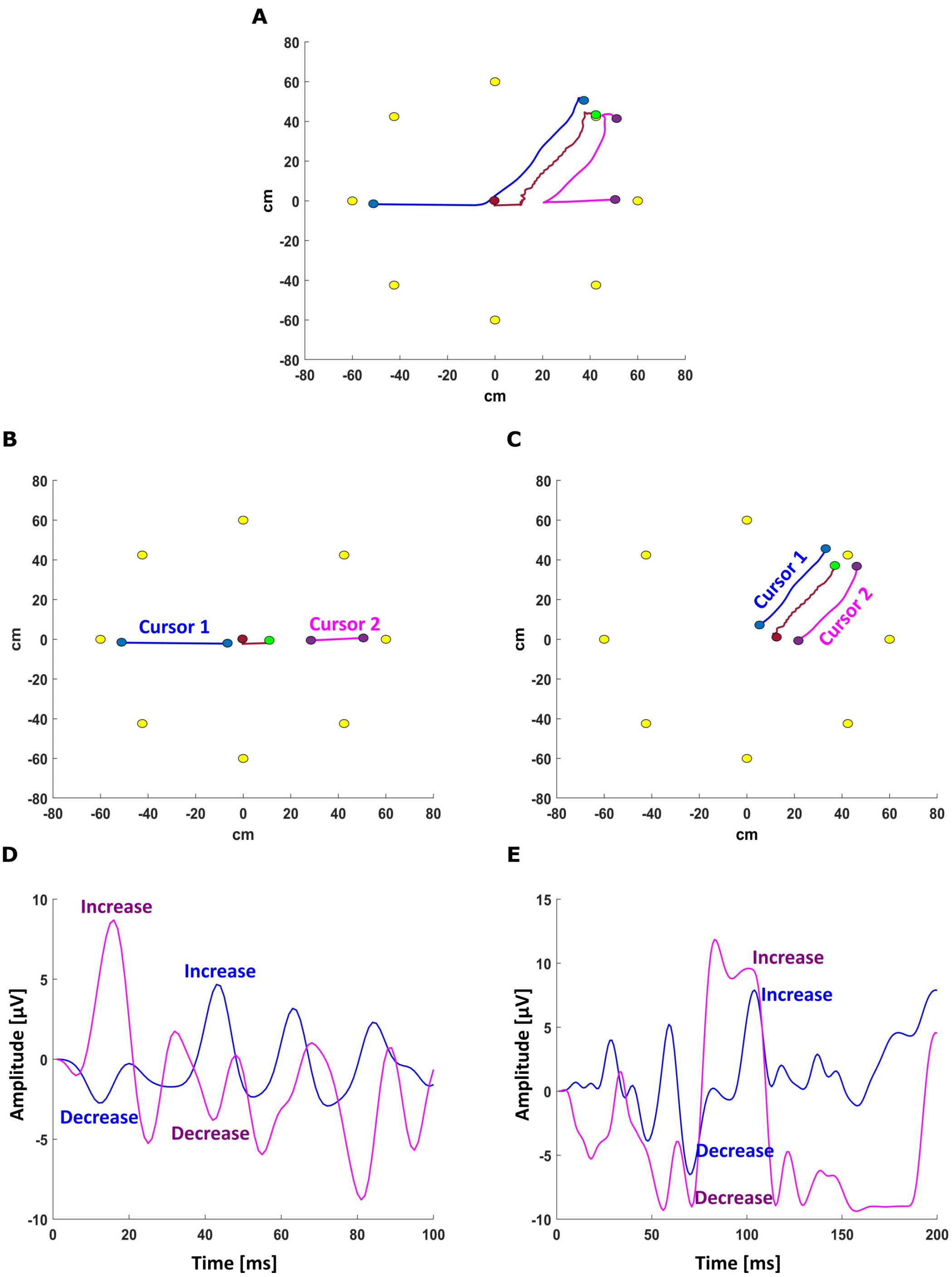

Figure 6.6: An example of Training session: No external force field. A target (yellow circle) appears at one of eight locations equally spaced at 45 degree on a circle around the home position of the joint cursor. Paired participants were asked to move the joint cursor (red circle) to a target (green circle). Blue and purple lines indicate the trajectories followed by each participant, whereas red line indicates the trajectory of joint cursor. (A) A typical example of trajectory (B) Sub-movements showing anti-phase synchronization in which paired participants moved their own cursor in the opposite direction. (c) Sub-movements showing in-phase synchronization in which participants moved their own cursor in the same direction. (D) Filtered EEG signals obtained within the time period including anti-phase synchronization. (E) Filtered EEG signals obtained within the time period including in-phase synchronization.

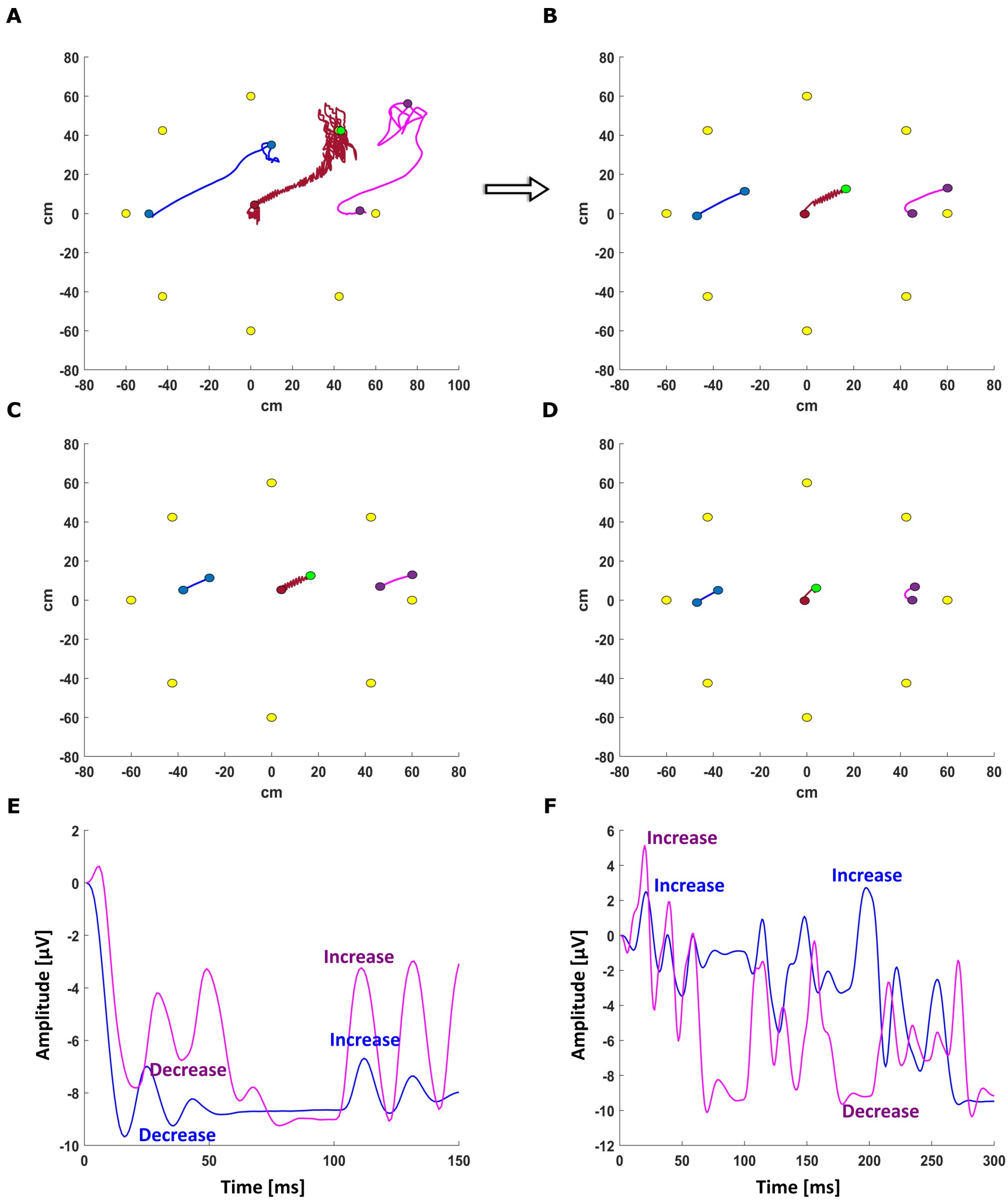

Figure 6.7: An example of Training session: Applied external force field. A target (yellow circle) appears at one of eight locations equally spaced at 45 degree on a circle around the home position of the joint cursor. Paired participants were asked to move the joint cursor (red circle) to a target (green circle). Blue and purple lines indicate the trajectories followed by each participant, whereas red line indicates the trajectory of joint cursor. (A) A typical example of trajectory (B) A sub-movement including in-phase and anti-phase synchronization. (C) and (D) show the sub-movements obtained by dividing the movement in (B) into two sub-movements. (E) Filtered EEG signals obtained within the time period when performing the sub-movement in (C). (F) Filtered EEG signals obtained within the time period when performing the sub-movement in (D).

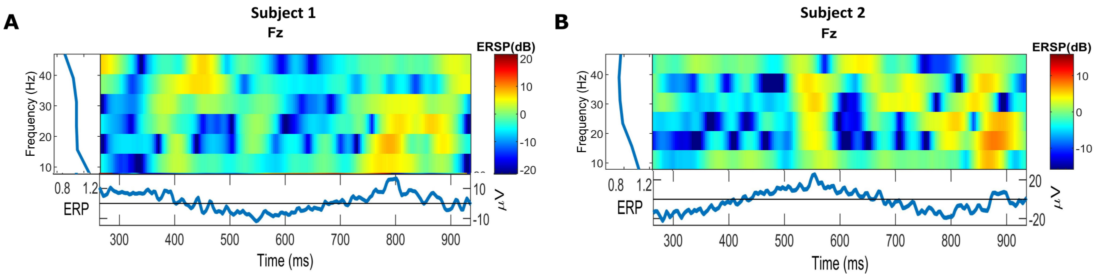

Figure 6.8: Example ERP image plots occurring in a single trial. ERPs recorded at electrode Fz in anti-phase synchronization (i.e. when subjects moved their own cursor in the opposite direction). (A) Subject 1. (B) Subject 2.

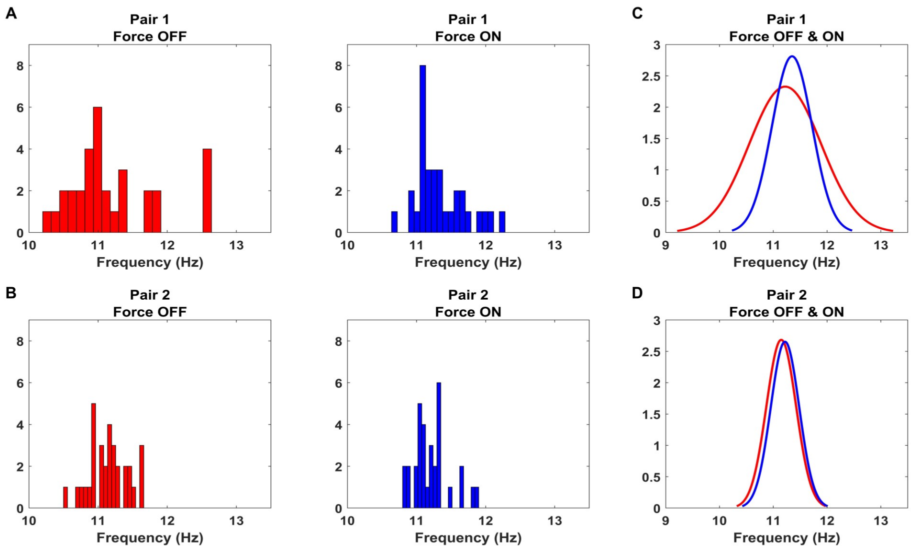

Figure 6.9: The distribution of Phi1 frequency over right centro-parietal region including CP2 and CP6. EEG data was taken from the first training-set of each Training session. Training session was performed in two different type: with (Force ON) or without external force (Force OFF). Red histogram and red curve indicate the Training session in the absence of the external force. Blue histogram and blue curve indicate the Training session in the presence of external force. (A) shows Pair 1 with histogram. (B) shows Pair 2 with histogram. Normal Gaussian frequency curve was obtained in each Training session for each pair to show the change in mean frequency. (C) shows Pair 1 (Force OFF: 11.22±0.66 and Force ON: 11.34±0.37). (D) shows Pair 2 (Force OFF: 11.14±0.27 and Force ON: 11.21±0.26).

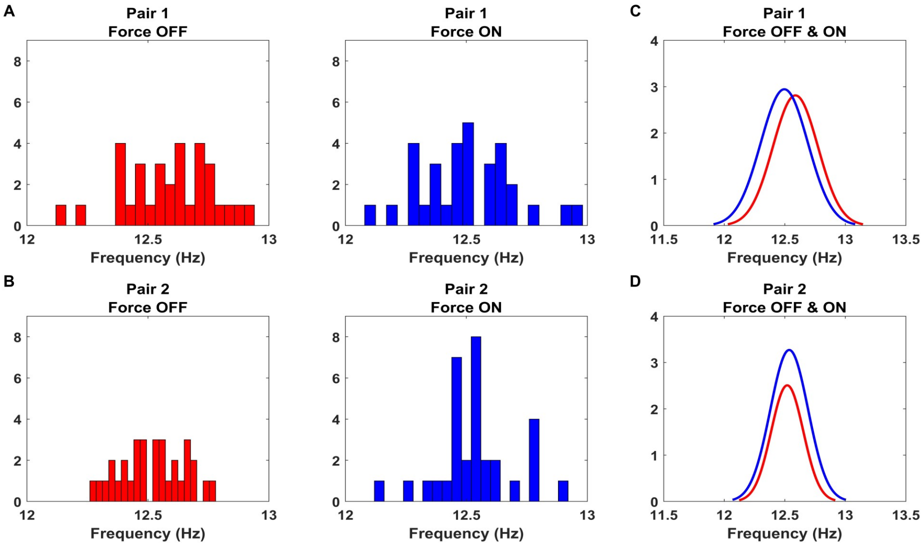

Figure 6.10: The distribution of Phi2 frequency over right centro-parietal region including CP2 and CP6. EEG data was taken from the first training-set of each Training session. Training session was performed in two different type: with (Force ON) or without external force (Force OFF). Red histogram and red curve indicate the Training session in the absence of the external force. Blue histogram and blue curve indicate the Training session in the presence of external force. (A) shows Pair 1 with histogram. (B) shows Pair 2 with histogram. Normal Gaussian frequency curve was obtained in each Training session for each pair to show the change in mean frequency. (C) shows Pair 1 (Force OFF: 12.58± 0.18 and Force ON: 12.49±0.19). (D) shows Pair 2 (Force OFF: 12.52±0.13 and Force ON: 12.53±0.15).

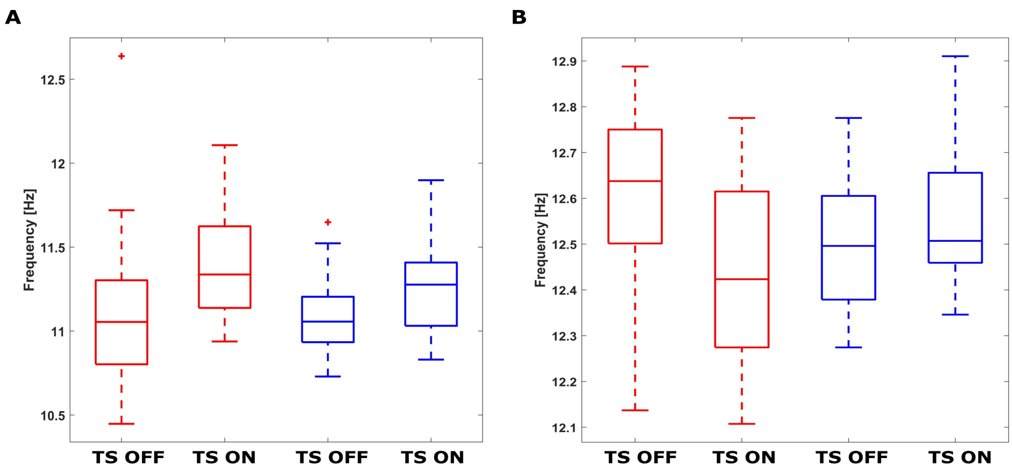

Figure 6.11: Boxplots comparing the frequency in Training sessions.Red boxplots indicate Pair 1 and blue boxplots indicate Pair 2. x-axis shows Training sessions; TS OFF: Training session in case external force field off and TS ON: Training session in case external force field on. y-axis shows frequency in Hz. (A) Phi1; Pair 1: $p=0.278$ and Pair 2: $p=0.0361<0.05$. (B) Phi2; Pair 1: $p=0.0416<0.05$ and Pair 2: $p=0.3322$.

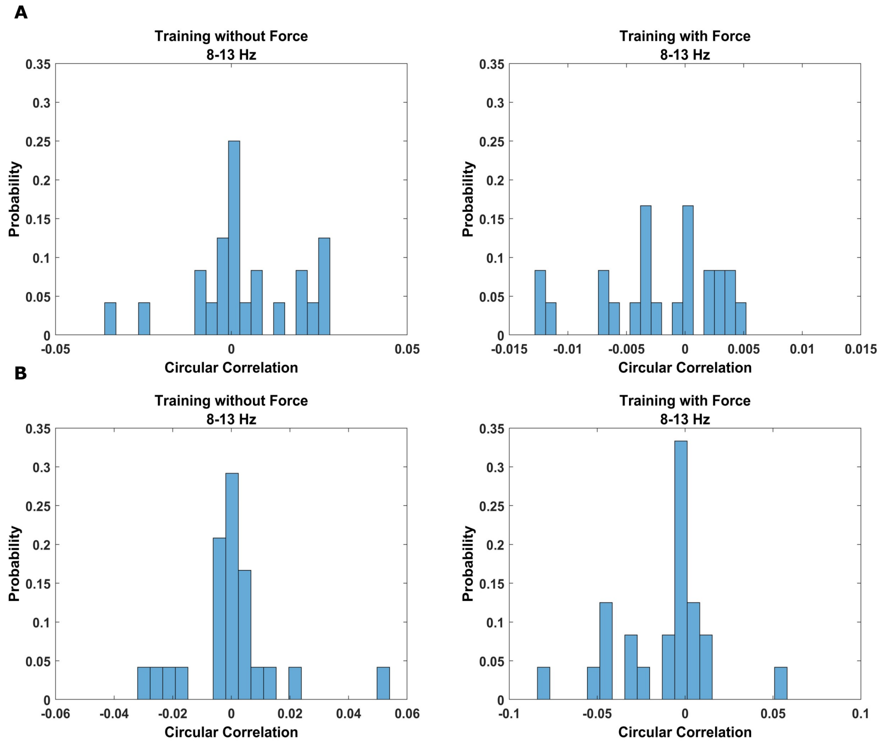

Figure 6.12: Distribution of surrogate circular correlations between members of pairs. Surrogate data was created by shifting EEG signals. EEG signals were filtered between 8-13 Hz. (A) shows Pair 1. (B) shows Pair 2.

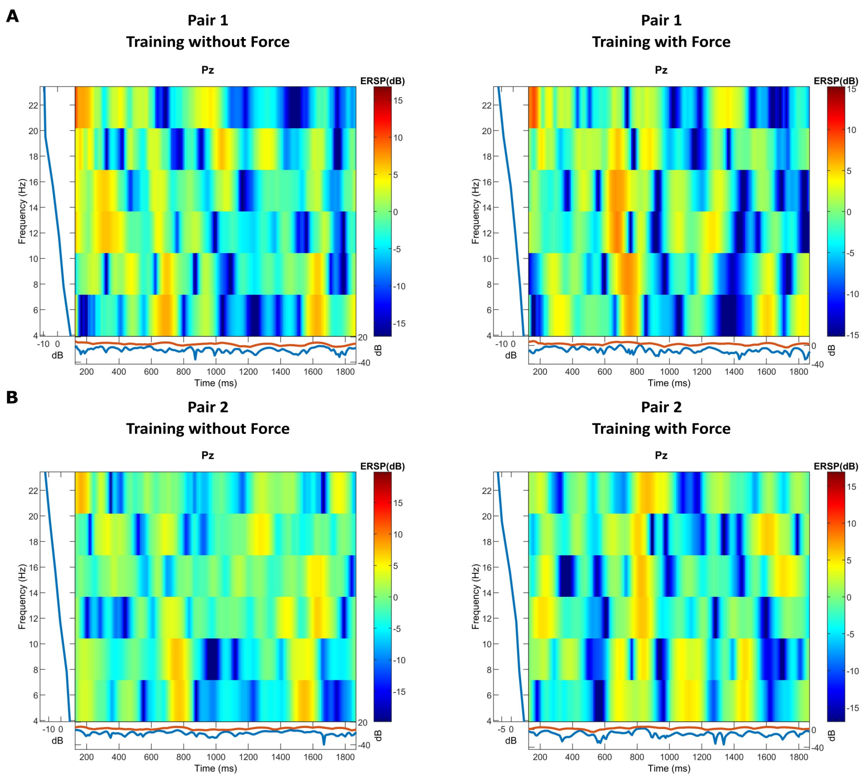

Figure 6.13: Beta power at channel Pz. (A) shows Pair 1. (B) shows Pair 2.

Chapter 7

Conclusion

Successful motor performance requires adaptation to changes in the interacting environment [21, 61]. The recent study [11] on skill learning raised a question about how to deal with instabilities occurring in the learning environment. While performing a motor task, humans can face dual instability arising from the interaction with others or environment. For instance, in sport activities or dance it is fundamental to adapt to changes in the interacting environment and other players' motion. While carrying a heavy object with others, there could be unconscious mutual adaptation. To date, the research on skill learning focused on understanding adaptation to virtual force fields in reaching tasks or visuomotor transformations.

7.1 Research Contributions

This PhD thesis aims to address the issue of dual instability with four interrelated projects: First, we investigated adaptation to others (adaptability) by employing a visuomotor task in which there was no haptic feedback. Our findings showed that practicing with another novice is more advantageous than practicing with an expert agent algorithm for adaptability to others. In the second study we designed a visuo-haptic motor task by which paired participants interacted with each other through the integration of visual and haptic feedback. In line with the first study, novice-to-novice interaction led to better adaptability than novice-to-expert interaction. The study, also, emphasized that mutual skill learning can occur only in case of adaptability.

Previous studies [6, 10, 11, 130] indicated the importance of dyadic interaction in skill learning such that dyads showed better performance than individuals. However, the necessary conditions to be able to learn dual dynamics (i.e. environmental and partner dynamics) has remained unclear. In the third study, the findings suggested that there could be a separation of dual dynamics in case of mutual haptic interaction, which facilitated mutual skill learning. It is known that more practice and high quality feedback enhance the process of skill learning [21]. Our findings, also, showed that active mutual interaction led to skill learning even in the presence of dual dynamics. It is important to note that haptic interaction was the only mode of communication between the paired participants in this study. Last but not least, EEG-hyperscanning study was performed to identify the neuromarkers of mutual skill learning in a cooperative motor task. Recently [1] Phi1 and Phi2 have been determined as a neuromarker of social coordination, such that Phi1 increased with independent behaviour, and Phi2 increased with coordinated behaviour. We found significant decrease in the Phi2 frequency band in case of no learning. We suggested that the decrease in coordinated behaviour due to the decrease in mutual haptic interaction would obstruct skill learning. Even though this is a pilot study, the result is consistent with the recent study [1] indicating the neuromarker of social coordination. To conclude, these studies suggest that skill learning happens in case of mutual haptic interaction.

7.2 Limitations

There are multiple limitations of this PhD project such as a limited sample size. The first three studies (chapter 3, chapter 4 and chapter 5) recruited thirty-two, twenty-three and thirty-five participants, respectively. The sample size is reasonable in these studies but it could be much larger. On the other hand, the EEG hyperscanning study (chapter 6) is a pilot study, in which only four participants took part. Much more experiment (at least with 10 participants) is needed to confirm our findings in this EEG study. In addition, the number of males was higher in the first study (chapter 3), whereas the number of females was higher in the third study (chapter 5). The second study (chapter 4) investigated the effect of training with an expert or a novice partner on motor skill learning. Here, the novice participant has no previous knowledge about the task and the expert has been previously trained with the task under the external force field as an individual by performing 180 and 120 trials in two consecutive days. In our study, the results demonstrated that performing 300 trials in total was enough to provide an appropriate level of expertise to a novice person. However, it is known that long practice with a task can result in more expertise with the task [21]. Therefore, the time for the practice could be a limitation. Also, the study recruited and trained only one participant as an expert, and the validity of the human expert could be another limitation; i.e. whether the human expert has been a true expert of the task, and whether the expert had always been able to interact with the participant in the same way, because human expert would have variability in motor coordination. Last but not least, the stiffness factors of the virtual springs were same in all these studies, which could be another limitation.

7.3 Applications

Motor skill learning is an important issue in rehabilitation in which physical therapists assist patients to relearn walking after stroke [61]. The recent technological advancements paved the way of the usage of robot-assisted motor skill acquisition algorithms in physical rehabilitation. Our findings are promising to understand the process of motor skill learning, develop effective strategies that will enhance motor skill learning [21], build robots in a human-like manner to assist patients [7, 41], and also design simulator for training of dental students, surgeons or players in a natural way [8]. Additionally, understanding human motor intention is important to design a direct brain computer interface (BCI) communication channel [131].

7.4 Future Work

The EEG hyperscanning study (chapter 6) is a pilot study, in which only four participants took part. First, much more experiment in our EEG hyperscanning paradigm (at least with 10 participants) is needed to confirm our findings. In the pilot study, a haptic robotic interface plays an important role as being the channel for mutual sharing of intentions. Next, different experimental conditions such as learning through haptic interaction, learning through visual interaction or learning under visual and haptic interaction could be tested using our EEG hyperscanning paradigm. Moreover, the stiffness factors of the virtual springs were same in all these studies. Our EEG hyperscanning paradigm could be tested by changing the stiffness factors.

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Appendix A

Experimental Setup

The experiment was set up in two separate identical rooms equipped with a LCD screen and a haptic arm (Fig.A.1). Participants seated in front of the screen with one-meter distance and hold the tip of the haptic arm (Fig.A.2) situated on the desk.

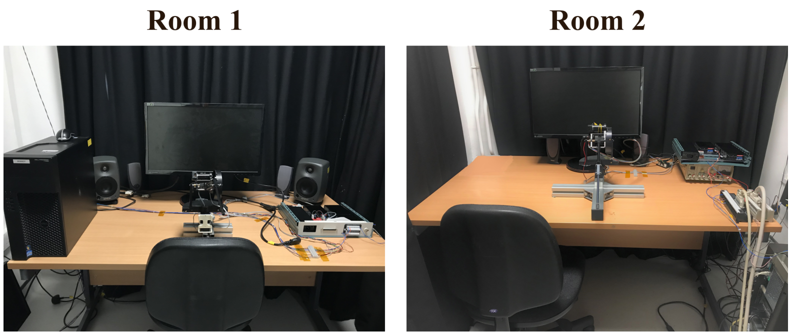

Figure A.1: Identical experimental rooms for each participant

To provide mutual haptic interaction between two participants, two haptic systems were developed. Each haptic system has the following hardware pieces:

- 1x 3DoF Phantom 1.5 (2DoF actuated)
- 2x DC Motor (Maxon 118743)
- 2x Encoder (HEDM-5500 Incremental Encoder)
- 1x Power Supply (XP Power - AHM150PS24)
- 2x Motor Controller (Maxon 250521, Servo amplifier, LSC 30/2 Series, 2A, 12 to 30Vdc)
- 2x DAC channels (CONTEC DA12-16(PCI))

- 2x Encoder channels (CONTEC CNT32-8M(PCI) & CONTEC EPD-96)
- 1x red PCB Emergency stop board

The robotic arms (3DoF Phantom 1.5) were created at Brain Embodiment Lab (BEL Lab) located in G60, Polly Vacher Building, University of Reading. The Phantom like robotic arms were used to translate participant's movement to the computer screen. Fundamentally, each haptic arm requires two DC motors resulting in large range of forces, two encoders as a sensing device of movement and two motor controllers to receive a command signal from the control system and transmit electric current to the motor.

Figure A.2: 3DoF Robotic Arm

As regards to the setup of haptic system (Fig.A.7), the encoders were connected to Counter Board (CONTEC CNT32-8M(PCI)) and the motor controllers (Maxon 250521) were connected to DA Board (CONTEC DA12-16(PCI)). The Counter Board and the DA Board were connected to an I/O Box (CONTEC PCIe 13 Slots) which was connected to xPC Target. As well as, xPC Target was connected to another PC called host PC. The communication between xPC Target and host PC was provided via UDP Ethernet.

Moreover, there are two motor controller boxes (Fig.A.3) including servo amplifiers (Maxon 250521), a power supply (XP Power AHM150PS24) and a red PCB emergency stop board. Each servo amplifier requires a power input connection (red / black), motor connection (brown / blue), set point (twisted pair) and a disable signal (yellow). Apart from the wiring, each servo amplifier was configured as stated in the data-sheet and the current limit was set to the maximum value of 2A.

The I/O Box contains up to 13 Peripherals Component Interconnect Express (PCIe) which allows external peripheral devices to be connected to a PC at the same time. There are seven PCIe cards installed in the I/O box. First, PCIe Bus Express enables the I/O box and other PCIe components to communicate with xPC Target, so xPC Target collects all the data produced by the peripherals. For each robotic arm

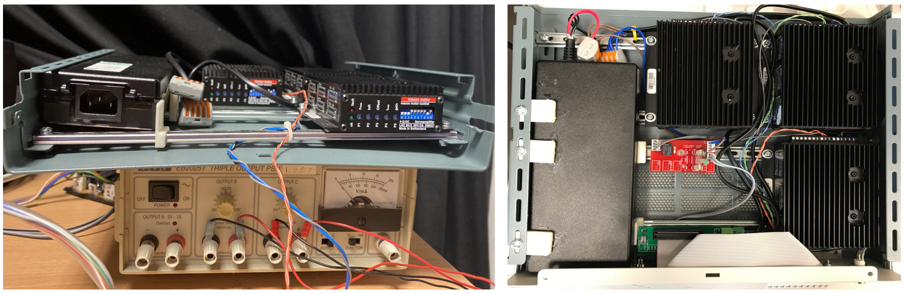

Figure A.3: The front and top view of motor controller box including three servo amplifiers, a power supply and a red PCB emergency stop board

two DAC-channel is needed. Thus, second, DA Board was installed into the I/O box to convert digital data to analogue data. In addition, four AD Board (Contec AD 12-16(PCI)) were installed to convert analogue data coming from amplifiers (gTec g.BSamp) to digital data. The last one is Counter Board used to make calculation of different angle in the robotic arm and convert these values to coordinates. The Counter Board has 8 channels. Each robotic arm requires two encoder channels (axis x and y).

To find the end-effector position of the robotic arms, the forward kinematics was calculated using Eq. (A.1).

$$T_n^{n-1} = \begin{bmatrix} cos\theta_n & -sin\theta_n & 0 & a_{n-1} \\ sin\theta_n cos\alpha_{n-1} & cos\theta_n cos\alpha_{n-1} & -sin\alpha_{n-1} & -d_n sin\alpha_{n-1} \\ sin\theta_n sin\alpha_{n-1} & cos\theta_n sin\alpha_{n-1} & cos\alpha_{n-1} & d_n cos\alpha_{n-1} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{A.1}$$

Identification of Denavit-Hartenberg (D-H) parameters is fundamental to compute Forward Kinematics equation.

Table A.1: Identification of Denavit-Hartenberg Parameters of 3DoF Robotic Arm

i	**q**	**d**	**a**	α
1	q_1	0	0	-π/2
2	q_2	0	L_1	0
3	q_3	0	L_2	0

The end-effector position of the each robotic arm ($[P_x,\ P_y,\ P_z]$) was found by using D-H parameters (Table A.1) and following equations (Eqs. (A.2, A.3, A.4).

$$P_x = sinq_1 * (L_1 * cosq_2 + L_2 * sinq_3) \tag{A.2}$$

$$P_y = L_1 * sinq_2 - L_2 * cosq_3 + L_2 \tag{A.3}$$

$$P_z = cosq_1 * (L_1 * cosq_2 + L_2 * sinq_3) \tag{A.4}$$

Regarding the real-time control of the haptic system, two nested programs (shown in Fig.A.4 and Fig.A.5) were developed in MATLAB Simulink 2015b (The MathWorks Inc., MA, USA) software and implemented with UDP Ethernet connection between Host PC and xPC Target.

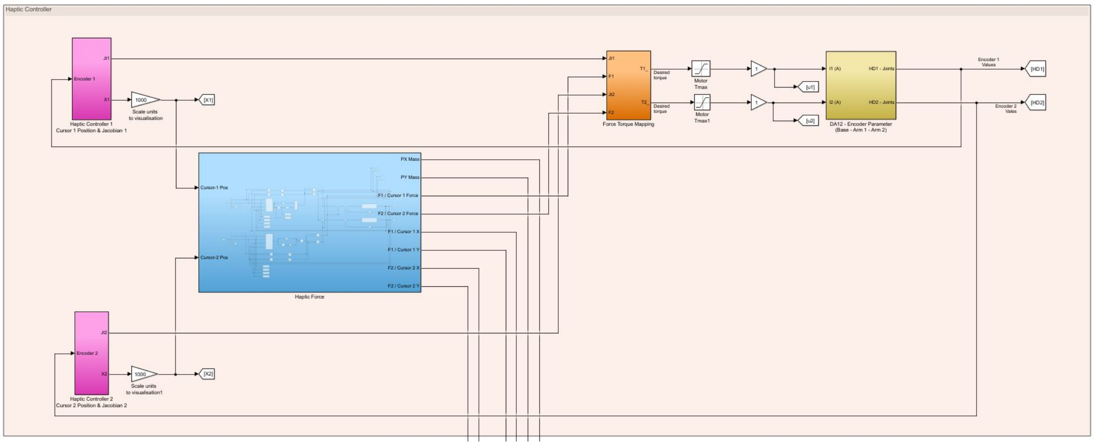

Figure A.4: Copy of the MATLAB Simulink program to provide haptic interaction between two-person

Whereas all the commands and the experimental paradigm were executed in Host PC, xPC Target was used to increase the speed of the task execution. MATLAB was used to display the experimental task (Fig.6.1) on the screen, and collect the following data:

- the position of cursor 1
- the position of cursor 2
- the position of joint cursor
- time when holding the joint-cursor on the target
- time when both two participants placing their own cursor onto the home position

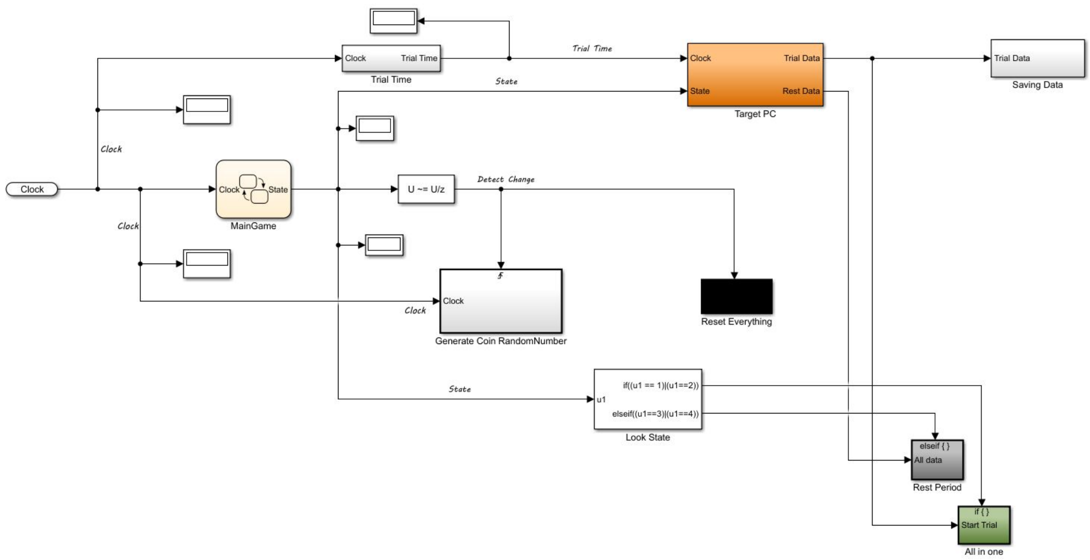

Figure A.5: Copy of the MATLAB Simulink program to develop a cooperative motor task

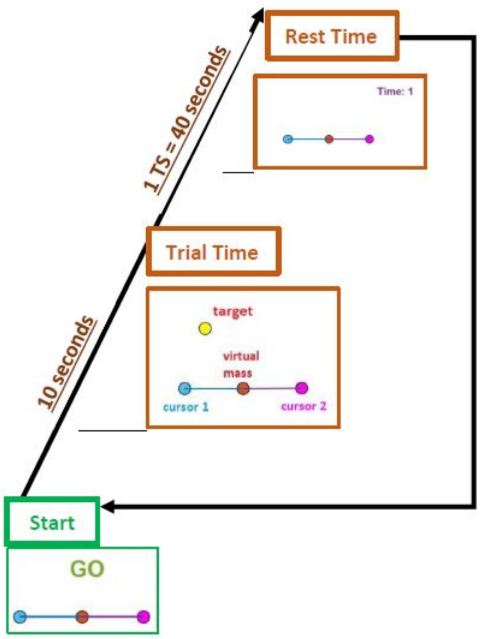

Figure A.6: A Training-set in the game: First the subjects see the screen called rest time for a 10-second. At the end of the rest time, subjects receive an instruction (e.g. Go signal on display) to start the game, and the screen called trial time appears. During the trial time, subjects were asked to move a virtual mass onto the target by controlling the robotic arm. When virtual mass crossed into the target, the screen of rest time appears again. The subjects were asked to move their own cursor on the home position and then hold it. The loop is repeated 10 times. After each 10 training-set, the subjects have a rest for one minute.

Regarding EEG system setup (Fig.A.7), g.Tec g.GAMMAbox was used to translate brain activity into signals. The analog EEG signals recorded using g.Tec g.BSamp were converted into digital signals through AD converter. The EEG data was collected using xPC Target, and saved in the Host PC for the further analysis.

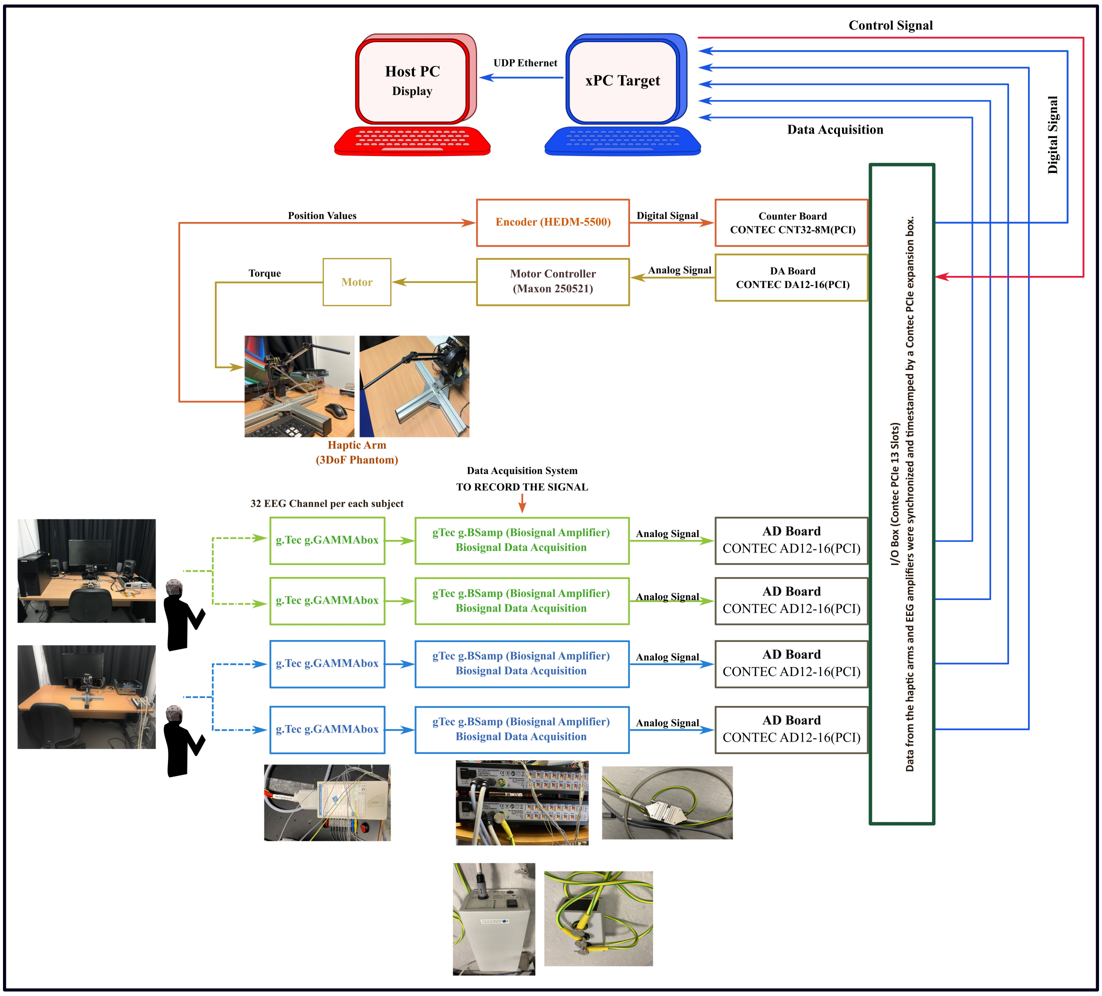

Figure A.7: Experimental Setup

Appendix B

Publications

B.1 Journal publications

Nishimura, K., Saracbasi, O. O., Hayashi, Y., and Kondo, T. (2021). Cooperative visuomotor learning experience with peer enhances adaptability to others. Adv. Robot. 35, 835–841. doi: 10.1080/01691864.2021.1913445

Saracbasi O.O, Harwin W, Kondo T and Hayashi Y (2021) Mutual Skill Learning and Adaptability to Others via Haptic Interaction. Front. Neurorobot. 15:760132. doi: 10.3389/fnbot.2021.760132

Saracbasi, O. O., Harwin, W., Kondo, T. & Hayashi, Y. (2023) Simultaneous Learning against to Sequential Learning via Haptic Interaction. Scientific Reports. (Submitted)

B.2 Presentations and Conference Abstracts

Saracbasi, O. O., Harwin, W., Kondo, T. and Hayashi, Y. (2022, August 29-31) Sequential Learning via Haptic Interaction. IV. International Agricultural, Biological & Life Science Conference, Edirne, Turkey. (Oral Presentation).

Saracbasi, O. O., Harwin, W., Kondo, T. and Hayashi, Y. (2022, July 11-15) Dual Instability against to Sequential Learning via Haptic Interaction. 44th International Engineering in Medicine and Biology Conference (EMBC), Glasgow, United Kingdom. (e-Poster Presentation).

Saracbasi, O. O., Kondo, T. and Hayashi, Y. (2021, September 1-3) Is it possible to learn new skills under two unknown dynamics? III. International Agricultural, Biological & Life Science Conference, Edirne, Turkey. (Oral Presentation).

Appendix C

Review on Skill Learning

Following table describes the studies on skill learning and haptic interaction with their results to provide a deeper understanding on the studies mentioned in the literature review (Chapter 2).

Table C.1: Summary of studies on Skill Learning

Article	Main Question	Subjects	Experimental Protocol	Outcome Measures	Main Results
van der Wel et al. 2011 [6]	How did dyads use haptic information for coordination?	54 participants - Solo task: 18 participants & Dyadic task: 36 participants	(1) Individual Performance (2) Dyadic Performance based on visual and haptic Information (No verbal communication) & 45 trials in total	(1) Force on each cord (2) Pole kinematics (3) Movement Periods	(1) Dyads produced much more overlapping forces than individuals (2) Dyads may deal with coordination difficulties using combination of haptic and visual information (3) Dyads amplify their forces to generate a haptic information channel to coordinate their movements.
Groten et al. 2013 [49]	Is it possible to integrate intentions through the exchange of haptic signals?	1st experiment: 24 participants & 2nd experiment: 58 participants	(1) Haptic-Feedback-from-Object-and-Partner based on visual and haptic feedback (2) Haptic-Feedback-from-Object based on only visual feedback, no force feedback & No verbal communication & white noise applied to remove the distractions caused by haptic interfaces	(1) Force on the virtual object (2) Individual force (3) Displacement between the desired and the actual position of the virtual object	Subjects could negotiate their intentions utilizing mutual haptic interaction.
Zenzeri et al. 2011 [34]	How the central nervous system switches between two stabilization strategies while performing an unstable task? SSS: a high-stiffness strategy & PSS: a low-stiffness positional strategy	1 participant	a novice practiced 11 sessions to be an expert	(1) Effort Index (2) Time to Target	(1) An expert can easily switch from one strategy to the other one (2) The amount of effort gradually decreased depending on the amount of practice.
Saha and Morasso 2012 [33]	Which one is the suitable stabilization strategy under an unknown dynamical task? - stabilization strategies: a high-stiffness strategy (SSS) & a low-stiffness positional strategy (PSS)	13 participants	(1) familiarization phase to introduce the experimental task in which force field presented along the y-axis (2) adaptation phase in which force field presented along the x-axis & 48 trials	(1) Body Weight (2) Body Mass Index (3) Maximum Grip Force (4) Stiffness Size Index (5) Stiffness Orientation Index	(1) SSS subjects applied large forces to increase stiffness - SSS: high-bandwidth & high-effort mechanism (2) PSS subjects applied force impulses which resulted in much more time to stabilize the mass - PSS: low-bandwidth & low-effort mechanism.
De Santis et al. 2014 [2]	How skill transfer and adaptation occur when paired subjects are required to switch from a bimanual to a dyadic configuration?	2 participants (1 Male and 1 Female)	SSS: a high-stiffness strategy & PSS: a low-stiffness positional strategy - 7 days including 2 sessions per day - each session including 24 reach-and-stabilize movements	(1) Effort Index (2) Time to Target (3) Mean Amplitude of the Velocity Peaks (4) Mean Effort Difference (5) Hand Synchronization Index	(1) Dyads are more advantageous to minimize the effort to perform the task using both SSS and PSS strategies (2) Complex motor skills can be transferred from a bimanual to a dyadic paradigm.

Article	Main Question	Subjects	Experimental Protocol	Outcome Measures	Main Results
Zenzeri et al. 2014 [32]	How humans be skilled users of a bi-manual tool in an unstable environment?	8 participants	2 Experimental Task; (1) 10 sessions including 2 target-sets (12 center-out movements and 12 return movements per set) performed using SSS and PSS respectively. (2) a single-session, tracking four differently shaped trajectories.	(1) Stiffness Size Index (2)Stiffness Orientation Index (3) Effort Index (4) Time to Target (5) Bimanual Separation Index (6) Magnitude of the Velocity Peaks (7) Frequency of the Velocity Peaks (8) Tracking Error	A novice can be trained to be an expert in both strategies (SSS and PSS) and to be able to switch from one to the other (e.g. SSS to PSS) in a natural way.
Ganesh et al. 2014 [10]	How the forces through physical interaction with a partner adapt the motor behavior?	74 participants	Single and Dual Trials - 4 sessions including 10, 20, 20 and 10 trials respectively. The two middle sessions include a visuo-motor rotation. The stiffness of the elastic band is 60, 120 or 180 N/m.	Trial Error	(1) Paired subjects achieved significantly better performance compared to individual performance. (2) The physical connection provides performance improvement even without awareness of a partner. (3) Performing with a novice partner is more advantageous than an expert. (4) A physical connection enhances motor performance regardless of their partner's performance.
De Santis et al. 2015 [31]	How the central nervous system selects an appropriate strategy to deal with environmental instabilities?	3 participants	2 experiments: (1) Bimanual training in which subjects trained to be an expert of the balancing task (2) Dyadic cooperation - 3 target sets including 24 reaching-and-stabilize movement trials.	(1) EMG data (2) Effort Index (3) Time to Target (4) Synchronization Delay	(1) The effort exerted by the experts is similar to the dyadic training. (2) Dyadic cooperation is more advantageous in performing the task but may be energy consuming.
Avila Mireles et al. 2016 [35]	How the different initial skill levels of the interacting partners influence the learning of a stabilization task?	12 participants including 10 novices and 2 expert (trained for 10 sessions)	2 Experimental groups: Naive-Naive and Expert-Naive - 5 experimental sessions in which 1-4: Training and the last one is Asssesment. A target set includes 16 stabilization movements within peripheral target.	(1) Effort Index (2) Time to Target (3) EMG	Training with an expert is more advantageous for the joint task, which is not transferred to the individual performance.
Takagi et al. 2016 [50]	Do paired subjects update their motion plan to reduce or increase interaction force to improve coordination?	16 participants (8 dyads)	135 trials in seven blocks: (1) a coupled block (30 trials) including reaching movements,(2) solo block (10 trials) in which subjects returned to baseline position, (3) push-pull block (30 trials) in which one pushed towards the target and the other pulled away	(1) Trajectory (2) Torque	Dyads do not coordinate during joint reaching movements towards the same target.

Article	Main Question	Subjects	Experimental Protocol	Outcome Measures	Main Results
Avila Mireles et al. 2017 [11]	How two people mutually exchange information to find the optimal trade-off between exploration and exploitation?	30 participants (28 novices and 2 experts)	3 session: (1) Priming Session (2) Training Session (3) Test Session - Each session includes 3 phases: (1) Familiarization (2) Training (3) Wash-Out	(1) Effort Index (2) Time to Target (3) Inefficiency Index (4) Mutual Information (5) Average RMS	(1) Training with another novice is more advantageous to learn a new skill. (2) If a novice has a prior experience with the unknown dynamics, the novice can learn the task with an expert. (3) Experts should give a chance to the novice to explore the unknown dynamics.
Takagi et al. 2017 [51]	How the haptic information is used to exchange movement information and adapt to partner's behaviour?	40 participants	4 Experimental Models: (1) Interpersonal Goal Integration (2) No Computation Model (3) Follow the Better (4) Multi-sensory Integration - 10 Trials (5 Alone - 5 Connected)	Tracking Error	(1) In connected trials motor performance improved for both partners regardless of their difference in skill level. (2) Physical Interaction enables one to infer the other's target from the motion.
Galofaro et al. 2017 [36]	Which is the best possible way for motor skill acquisition; through observation or physical training with an expert?	19 participants (18 novices and an expert)	2 sessions: (1) Dyadic performed with an expert - including 10 target sets (2) Bimanual Transfer performed as an individual - including 3 target sets - each target set includes 16 center-out-center movements - considering only Stiffness Stabilization Strategy (SSS) to be learned by novice subjects	(1) Effort Index (2) Time to target (3) Inefficiency Index (4) Gain Variation	It is important to balance exploration of environment and exploitation of an expert to generalize the task.
Takagi et al. 2018 [52]	How people modify their coordination strategy depending on the coupling strength to the partner?	14 pairs	(1) Follow the Leader: following the one who is closer to the target (2) Interpersonal Goal Integration based on Haptic and Visual feedback (3) Neuromechanical Goal Sharing based on the weighting the visual information and the haptic information - 45 trials in 3 blocks - 3 different strength of the elastic spring: (1) Hard (2) Medium (3) Soft	(1) Tracking Error (2) Effort	(1) The strength of coupling dynamics affected the quality of haptic information (2) To infer the partner's movement intention does not depend on the strength of coupling dynamics (3) Hard Interaction providing a better prediction of the partner's movement improved the performance
Takagi et al. 2019 [28]	How dyads, triads and tetrads coordinate their movements when each person is influenced by the force of others?	72 subjects	(1) No Exchange Model: no interaction force - tracking target using the visual information (2) Neuromechanical Goal Sharing Model based on the combination of the haptic information of the partner's target position and the visual information	Tracking Error	(1) The stronger stiffness improved the performance, decreasing the tracking error (2) The performance improvement depends on the group size, increasing with the group size (3) Dyads, triads and tetrads showed similar adaptability, regardless of the group size

Appendix D

Ethical Approval

Ethical approval for each experiment was given by the School of Biological Sciences, University of Reading. The accepted ethical request forms are presented below.

SBS Local Research Ethics Committee

Project Submission Form

Note All sections of this form should be completed.
Please continue on separate sheets if necessary.

Principal Investigator: Yoshikatsu Hayashi and William Harwin

School: School of Biological Sciences

Email: y.hayashi@reading.ac.uk

Title of Project: Transferring Skills via Haptic Interaction

Proposed starting date: 10th of March

Brief description of Project:

Skill means a learned ability through observation or training. Skill acquisition process includes three stages. Firstly, humans learn how to perform the task, which can be thought as learning the theory of the task. In the second stage, people start to try doing this task. After the stages regarding theory and practice, people can perform the task automatically. Driving a car, dancing or playing sports can be given as an example of skills. Skill transfer is a method in which the trainer teaches a person how to perform a new task or skill.

Previous research (Avila Mireles et al., 2017, 'Skill learning and skill transfer mediated by cooperative haptic interaction') has shown that when two people cooperate with each other to achieve a joint task (a task requiring coordination and cooperation between the partners like carrying a heavy table or dancing tango), they faced dual instabilities arising from the environment (i.e. unknown environment with external nonlinear forces) and interaction with a partner (i.e. the person performing the task together).The study has proven that performing a joint task with an expert (a subject that completed the learning process in previous experiments) leads to the greatest performance compared to a novice (a subject who has no experience). Also, the skills acquired from a joint task can be transferred to an individual performance only if the non-expert subject had prior experience about the dynamics of the task.

As explained above, the previous research examined the process of learning the dynamics of the environment for the better motor coordination under a cooperative task. We will investigate people how to learn their partner motion for the better motor coordination under a cooperative task. While the previous research has explained the process of learning the environmental dynamics by applying bimanual configuration (performed a task by a person using both hands) and dyadic configuration (performed a task by two people together), this study will examine the process of learning the partner's motion with only paired participants.

People are able to perceive the reactions of their surroundings via visual, verbal and haptic interaction and respond them. In the context of coordination tasks in unknown environments, people need to predict their partner's feedback to control their motion. Haptic robotic interface plays an important role as being the channel for mutual sharing of intentions. Haptic interaction is generated by using the virtual springs in this experiment like in the previous study (Avila Mireles et al., 2017, 'Skill learning and skill transfer mediated by cooperative haptic interaction').

The project aims to understand the process of learning the partner's motion for the better motor coordination under a cooperative task. The experiment will investigate the process by applying a simple target reaching task performed by participants using a Phantom Haptic Arm.

The experiment will be performed in three days with 20 participants at Brain Embodiment Lab (BEL), in G60, Polly Vacher building. The experimental protocol requires three days considered as respectively baseline, learning and evaluation. The participants will be grouped randomly in the beginning of the experiments. In the first day, participants will be asked to hold the cap of the haptic device created at BEL lab and control the cursor to bring the joint-cursor to randomly placed target. In the second day, the paired participants will be swapped, and they will perform the same task again. In the last day, they perform the same task with their same partner as in the first day. The session can be thought as evaluation. At the end of each experiment, each participant will be asked to answer a post experiment questionnaire designed to collect information about the social aspects of the experiment. Each session of this study will last approximately 40 minutes. During the task, experimenters will record the position, velocity, forces and the resulting acceleration.

I confirm that to the best of my knowledge I have made known all information relevant to the School Research Ethics Committee and I undertake to inform the Committee of any such information which subsequently becomes available whether before or after the teaching/research has begun.

I confirm that if this project is an interventional study, a list of names and contact details of the subjects in this project will be compiled and that this, together with a copy of the Consent Form, will be retained within the School for a minimum of five years after the date that the project is completed.

Signed:

…………… Yoshi ……………………………….. Date: ………………….…………………

(Investigator)

…………………………………………………….... Date: ………………….…………………

(Head of School or authorised Head of Department)

…………………………………………………….... Date: ………………….…………………

(Student -where applicable)

Checklist

1. This form will be submitted to the School Research Ethics Committee and will subsequently, if approved, be signed by my Head of School (or authorised Head of Department) ☑

2. The Consent form includes a statement to the effect that the application has been reviewed by the School Research Ethics Committee and has been given a favourable ethical opinion for conduct ☑

3. I have made, and explained within this application, arrangements for any confidential material generated by the teaching/research to be stored securely within the University and, where appropriate, subsequently disposed of securely. ☑

4. I have made arrangements for expenses to be paid to participants in the research, if any, OR, if not, I have explained why not. ☑

5. EITHER

   (a) The proposed teaching/research does not involve the taking of blood samples; ☑

   OR

   (b) For anyone whose proximity to the blood samples brings a risk of Hepatitis B, documentary evidence of immunity prior to the risk of exposure will be retained by the Head of School or authorized Head of Department. ☐

   Signed:

   ………………………………………….. Date……………………

   (Head of School or authorised Head of Department)

6. EITHER

   (a) The proposed teaching/research does not involve the storage of human tissue, as defined by the Human Tissue Act 2004; ☑

   OR

   (b) I have explained within the application how the requirements of the Human Tissue Act 2004 will be met. ☐

7. EITHER

   (a) The proposed teaching/research will not generate any information about the health of participants; ☑

OR

(b) If the teaching/research could reveal adverse information regarding the health of participants, their consent to pass information on to their GP will be included in the consent form and in this circumstance I will inform the participant and their GP providing a copy of the relevant details to each and identifying by date of birth; ☐

OR

(c) I have explained within the application why (b) above is not appropriate. ☐

8. EITHER

(a) the proposed research does not involve children under the age of 5; ☑

OR

(b) My Head of School (or authorised Head of Department) has given details of the proposed research to the University's insurance officer, and the research will not proceed until I have confirmation that insurance cover is in place. ☐

Signed:

………………………………………….. Date………………..…

(Head of School or authorised Head of Department)

This form and further relevant information (consent form and information sheet) should be returned electronically to:

Dr M. Alejandra Perotti
Email: m.a.perotti@reading.ac.uk

You will be notified of the Committee's decision as quickly as possible, and you should not proceed with the project until a favourable ethical opinion has been passed.

School of Biological Sciences

Application Form

SECTION 1: APPLICATION DETAILS
1.1 Project Title: Transferring Skills via Haptic Interaction Date of Submission: Proposed start date: 10/March/2019 Proposed End Date: 10 /March/2020
1.2 Principal Investigator [supervisor name, if student project]: Prof Yoshikatsu Hayashi Office room number: 157 Internal telephone: 6701 Email address: y.hayashi@reading.ac.uk Other applicants (role): Ozge Saracbasi (PhD Student) Department: Biological Science Email address: o.o.saracbasi@pgr.reading.ac.uk
1.3 Project Submission Declaration I confirm that to the best of my knowledge I have made known all information relevant to the Research Ethics Committee and I undertake to inform the Committee of any such information which subsequently becomes available whether before or after the research has begun. I understand that it is a legal requirement that both staff and students undergo Criminal Records Checks when in a position of trust (i.e. when working with children or vulnerable adults). I confirm that a list of the names and addresses of the subjects in this project will be compiled and that this, together with a copy of the Consent Form, will be retained within the School for a minimum of five years after the date that the project is completed. Signed…………………………… (Principal Investigator) Date:………… Signed…………OzgeOzlem…… (Student) Date:…………

1.4

University Research Ethics Committee Applications

Projects expected to require review by the University Research Ethics Committee must be reviewed by the Chair of the School Ethics Committee or the Head of School before submission.

Signed………N/A………… (Chair of School Committee) Date:…N/A…………

Signed………N/A…………… (Head of School) Date:…N/A………

1.5

External research ethics committees

Please provide details below of other external research ethics committees to which this project has been submitted, or from whom approval has already been granted [e.g. NHS Committee]

Name of committee	Date of submission/approval	Reference	Status
N/A	N/A		

SECTION 2: PROJECT DETAILS

2.1

Lay summary

The experiment will be performed with pairs in three sessions. The participants will sit in separate rooms during the experiment, and the interaction between the participants will be provided through a haptic device and virtual spring. In this experiment, participants will be asked to hold the end-effector of the haptic device created at BEL lab (shown the photo of the haptic device in Figure 1) and control the cursor to bring the joint-cursor to randomly placed target.

Figure 1.Haptic Device (created at BEL Lab)

The end-effector of the haptic device will be covered with silicon, so it will not harm to participant's hand while performing the task. The force of the virtual spring between the haptic devices will be lower than 5 N, thus the force will not be harmful for the participant's arm. In addition to these, this haptic device has normally three-dimension freedom degree, but we will use two-dimension, and it will not twirl automatically. That is to say, the experiment will not damage to the participants. (The experimental set-up is shown below in Figure 2.)

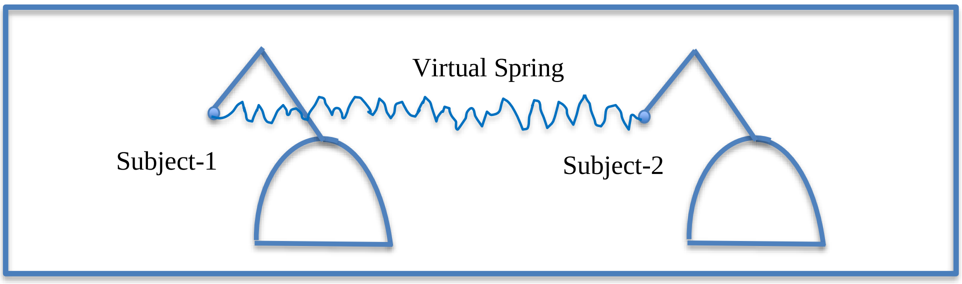

Figure 2. Experimental Set-up

The aim in this task is to bring the object to the target position. Four different conditions will be performed and tested in this experiment corresponding to a different number of targets on the screen respectively one target, two targets, five targets and ten targets. Each condition is repeated ten times. In total, each experiment consists of 40 trials, and each trial lasts 40 seconds. One-minute rest periods are given after every ten trials. The total duration of each session will be approximately 40 minutes.

2.2

Procedure

The experiment in which we will investigate the process of learning the partner's motion for the better motor coordination under a cooperative task will include 3 sessions (3 days). Each session will be performed with pairs, and each session includes 4 stages respectively: introduction, familiarization, training and evaluation. For the experiment, we will be collecting data from 20 participants.

Firstly, participants will be grouped as seen in Figure 3 (shown below). It is important that the participants have not met each other before. In the first day (The session of 'Baseline'), participants will perform a reaching task designed with 'MATLAB' software. After the participants perform the experiment in the first day, they will be swapped as seen in the Figure 3. For example, subject A will execute the task with subject D instead of subject B on the day 2. The swapped people will perform the same experiment in the second day (The session of 'Learning') so that the effects of the presence of another person in learning process will be explained. The other session is 'Evaluation'. In this session, the pairs in the first day will be employed again to evaluate their individual adaptabilities. In the three sessions the aim will be clarifying the difference of adaptability between the groups. The payment for the participation will be made if the participant attends all three sections to prevent partner's unavailability in later sessions.

Day - 1	Day - 2	Day - 3
A-B	A-D	A-B
C-D	C-B	C-D
E-F	E-H	E-F
G-H	G-F	G-H
I-J	I-L	I-J
K-L	K-J	K-L
M-N	M-P	M-N
O-P	O-N	O-P
R-S	R-U	R-S
T-U	T-S	T-U

Figure 3. The Participant Groups

As mentioned before, each session includes 4 stages respectively: introduction, familiarization, training and evaluation. (The stages can be seen with details below in Figure 4.)

Figure 4. Stages of the Experiment

1st Stage: Introduction to the participants (5 minutes)

In this stage, participants will be informed about the experiment. The details of the experiment such as how to perform the experiment will be explained to the participants.

2nd Stage: Familiarization (5 minutes)

Participants will try to bring the object to the target position before the experiment by using the instructions given in the stage of 'Introduction', so that they can familiarize with the study.

3rd Stage: Training Period (20 minutes)

Participants will perform the study with their pairs by using the haptic device created at the BEL Lab. Four different conditions will be performed and tested in this experiment corresponding to a different number of targets on the screen respectively one target, two targets, five targets and ten targets in the same order in every session. Each condition is repeated ten times. In total, each experiment consists of 40 trials, and each trial lasts 40 seconds. One-minute rest periods are given after every ten trials. The screen of this study will be seen as shown in Figure 5.

This experiment includes a type of cooperative task. In the cooperative tasks, increasing the number of the targets could lead to confusion. Also, the experiment needs coordination between the people so that they can predict their partner's feedback to control their motion. This experiment will apply haptic robotic interface for a channel to share intentions. In other words, the aim to select a different number of targets will be testing the haptic interface.

4th Stage: Evaluation Period (10 minutes)

The participants will be asked to fill in a questionnaire aimed at understanding each participant's impressions during the experiment at the end of the experiment.

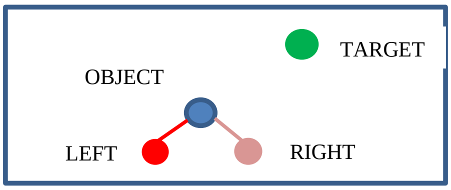

Figure 5. The screen of the study

The screen of this study will be seen as shown in Figure 5. As mentioned before, the participants will sit in separate rooms. In this figure, left refers to the left cursor (the robotic device in the left room), and right refers to the right cursor (the robotic device in the right room). Object means the joint-cursor which will be connected to the left cursor and right cursor with the virtual springs. The aim in this study is to control the cursor to bring the joint-cursor to randomly placed target (shown as a green circle in Figure 5).

Also, during the task, experimenters will record the position, velocity, forces and the resulting acceleration. The time and position values in three days will be compared by ANOVA statistical test. It is important that the consent and information forms will be given to the participants prior to enrolling on the study.

The research and experiments will be conducted by 1st year PhD student Ozge Saracbasi, who is supervised by Dr Yoshikatsu Hayashi, and Prof William Harwin, School of Biological Sciences.

2.3

Location

The experiment will take place in the Brain Embodiment Lab (BEL) located in G60, Polly Vacher building. There is a comfortable seating for the participant, the ambient lighting is proper, and monitors are kept at safe distance to avoid stress on eyes. Enough breaks will be given to the participants. There are no major risks associated with the experiment. The experiment operator will be present with the participant at all times.

2.4

Funding

This project is supported by Ministry of Education, Turkish Republic.

2.5

Ethical Issues

There are no ethical issues, apart from matters related to data storage, usage and confidentiality – these are discussed in Sections 2.8 and 2.9.”

2.6

Deception

This study does not involve deception.

2.7

Payment

Participants will be remunerated for their participation and time with £10 per each session.

2.8

Data storage, data protection and confidentiality

Data collected in this experiment is of two categories- 1) Digital: Kinematic and Haptic data. 2) Hard copy: questionnaire.

1) Digital data storage and confidentiality

a. *Kinematic and Haptic data:* Kinematic and haptic data will be stored using the anonymous user ID. The files will be stored in the secure shared BEL drive detailed above indefinitely, accessible to members of the research team.

2) Hard copy of questionnaire:

a. *Questionnaire:* Questionnaire asks for age, gender and handedness of the participants along with the confirmation that they have normal/corrected to normal vision, no motor or communication impairments and no medications affecting brain chemistry. The questionnaire is also targeted at determining the level of cooperation between participants. The aggregate of this information is required for publishing the scientific results of this study. Questionnaire itself will not be shared with anybody. Questionnaires will be anonymised with the unique identifier of the participant just like kinematic data. Questionnaires will be stored securely in BEL in a locked cabinet dedicated for this purpose, separate from the cabinet for consent forms.

2.9

Consent

Written information sheet outlining the experiment procedure will be presented to the participant. Experiment would be explained to the participant by the researcher and then the written consent would be obtained from the participants by completing the consent form at the beginning of the experiment. Participants reserve the right to withdraw from the experiment at any time without giving any reason.

The consent form is the only document that will contain the participant's name. Signed consent forms will be stored securely in the locked cabinet storage facility in BEL dedicated for this purpose. Consent forms will not be shared with the third parties.

The consent forms will be stored for 5 years after completion of the PhD, and then destroyed securely.

SECTION 3: PARTICIPANT DETAILS

3.1

Sample Size

Target sample size of the participants in this behavioural experiment is 20 and 120 trials of reaching the target position will be recorded from each participant. This was selected to get statistically significant results. Similar sample size is used in behavioural research on healthy humans according to the literature review. Sample size of this experiment was calculated using the following formula for 95% confidence level and 5% confidence interval:

$$\textit{Sample size} = ((\textit{z-score} * SD*(1-SD))/\textit{error margin})^2$$

Where, z-score for 95% confidence level is 1.96, standard deviation is unknown and hence considered as 0.5 and the error margin is ±5%.

3.2

Will the teaching/research involve vulnerable adults (e.g., adults with mental health problems or neurological conditions)?

NO.

3.3

Will your teaching/research involve children under the age of 18 years? NO

Will your teaching/research involve children under the age of 5 years? NO

3.4

Will your research involve NHS patients, NHS staff or Clients of Social Services? NO.

3.5

Recruitment

Participant recruitment will be done by advertising using emails and poster.

Researcher (principal): Dr Yoshikatsu Hayashi
Email: y.hayashi@reading.ac.uk
Phone: +44 (0) 118 378 6701

Researcher (role): Ozge Saracbasi (PhD Candidate)
Email: o.o.saracbasi@pgr.reading.ac.uk

School of Biological Sciences
Biomedical Engineering Section
University of Reading
Reading RG6 6AY

Phone: +44 (0) 118 378 8072
email: biosciences@reading.ac.uk

INFORMATION SHEET

Project Title: Transferring Skills via Haptic Interaction

Why are we doing this study?

People can perceive the reactions of the people in their surroundings via visual, verbal and haptic interaction and respond to them. Previous research (Avila Mireles et al., 2017, 'Skill learning and skill transfer mediated by cooperative haptic interaction') examined the process of learning the dynamics of the environment for better motor coordination under a cooperative task. We will investigate how people learn a partner's motion for better motor coordination under a cooperative task. While previous research has explained the process of learning the environmental dynamics by applying bimanual (a person performing a task using both hands) and dyadic (two people performing a task together) configurations, this study will examine the process of learning the partner's motion with only paired participants (The paired participants will be swapped in other session).

What is the purpose of the study?

We will investigate the process of learning the partner's motion for better motor coordination under a cooperative task with paired participants. The experiment will be performed over three days with 20 participants. The study aims to understand that how people learn their partner's motion in a cooperative task by using robotic device. The robotic device can be thought as a way to share people's intentions to each other. With the help of this study, we will evaluate people's individual adaptabilities in a joint task.

Who is eligible to participate in the study?

We are looking for healthy volunteers who

- Are 18 years old or older
- Have normal or corrected to normal vision
- Do not have any motor or communication impairing disabilities and,
- Are not taking any medications affecting brain chemistry.

How can you get involved?

If you would like to participate, please email Ozge Saracbasi at o.o.saracbasi@pgr.reading.ac.uk.

Do I have to take part?

Participation is entirely voluntary, and you can withdraw at any time without giving a reason, and this will be without detriment.

What will be involved if you take part?

The experiment involves three sessions over three days, when you will be asked to perform tasks with a partner who will be randomly chosen and assigned to work with you. Each session of the experiment lasts approximately 40 minutes. In all sessions, participants will be asked to hold the tip of a robotic device created in our lab and, together with their partner, move a cursor to a randomly placed target on the computer screen. The robotic device can be thought as a way to share people's intentions to each other. The robotic devices used by two participants will be connected with virtual springs. That is to say, the participants' movements will be affected their partner's movements by using robotic device and virtual spring. Four different conditions will be performed and tested in this experiment corresponding to a different number of targets on the screen (one target, two targets, five targets and ten targets). Each condition is repeated ten times. In total, each experiment consists of 40 trials, and each trial lasts 40 seconds. One-minute rest periods are given after every ten trials. We will record the forces along with acceleration, position and velocity during the experiment, and we also request you fill in a brief questionnaire after you have completed the trials.

Prior to starting the experiment, you will be asked to provide written informed consent and to complete a questionnaire about your gender, date of birth and handedness.

Confidentiality, storage and disposal of information

You will be asked to provide your name and to sign a consent form so that we can keep a record of your participation in the study, however, this information will be kept confidential and will not be disclosed publicly. The consent form will be stored in a locked filing cabinet in our lab, and destroyed securely 5 years after completion of the project.

All data from the study will be stored, processed, and reported using an anonymous user ID and as a part of an aggregate dataset collected from multiple participants. Hardcopies of the questionnaire will be transcribed into electronic form, and the hardcopies stored in a locked filing cabinet in our lab, separate from the consent forms, and destroyed 5 years after completion of the project. The questionnaire data will be used to understand the relationships that emerge between you and your study partner and will not be used to identify you in any way.

Anonymised Haptic data will be stored securely and password protected on the internal Brain Embodiment Lab server provided by the university, accessible to members of the research team now and in the future.

Are there any benefits/risks to taking part [e.g. health]?

There are no benefits or health risks to taking part in this experiment. However, you might feel fatigue because of the repetition movement of reaching a target.

What will the results of the study be used for?

The results of this study will contribute towards PhD research and scientific publications. If you would like to learn the results at the end of the study, please contact the researchers.

What payment will be made for participation in the study?

You will be remunerated for your time and participation with £10 for each study.

Where will the studies take place?

The study will take place in the Brain Embodiment Lab, Biomedical Engineering, located in the Polly Vacher building on the University of Reading's Whiteknights campus. A researcher will contact you to provide further directions, and to arrange a time slot for you.

Who has reviewed the study?

This project has been subject to ethical review, according to the procedures specified by the University Research Ethics Committee and has been given a favourable ethical opinion for conduct.

Contact details for further questions:

Experiments and the research will be conducted by Ozge Saracbasi (o.o.saracbasi@pgr.reading.ac.uk) who is currently a 1st year PhD researcher in Biological Science.

Ozge is supervised by Dr Yoshikatsu Hayashi and Prof William Harwin.
Contact details: PI Name: Yoshikatsu Hayashi
Email: y.hayashi@reading.ac.uk Phone: +44 (0) 118 378 5024

In the event of a complaint

If you have any comments or if you have a complaint, you can contact the Chair of the Ethics Committee of the School of Biological Sciences, Dr M. Alejandra Perotti Email: m.a.perotti@reading.ac.uk

Thank you for your help.

Investigator Contact Details:

Dr. Yoshikatsu Hayashi	Ozge Saracbasi
e: y.hayashi@reading.ac.uk	e: o.o.saracbasi@pgr.reading.ac.uk
	m:

Appendix C: data protection for information sheets

To be added to all participant information sheets. Please note, if you are providing this information to children, or individuals that may need more simple terms to help them understand this information please amend to suit your audience. If you need advice please contact imps@reading.ac.uk

The organisation responsible for protection of your personal information is the University of Reading (the Data Controller). Queries regarding data protection and your rights should be directed to the University Data Protection Officer at imps@reading.ac.uk, or in writing to: Information Management & Policy Services, University of Reading, Whiteknights, P O Box 217, Reading, RG6 6AH.

The University of Reading collects, analyses, uses, shares and retains personal data for the purposes of research in the public interest. Under data protection law we are required to inform you that this use of the personal data we may hold about you is on the lawful basis of being a public task in the public interest. If you withdraw from a research study, which processes your personal data, dependant on the stage of withdrawal, we may still rely on this lawful basis to continue using your data if your withdrawal would be of significant detriment to the research study aims. We will always have in place appropriate safeguards to protect your personal data.

If we have included any additional requests for use of your data, for example adding you to a registration list for the purposes of inviting you to take part in future studies, this will be done only with your consent where you have provided it to us and should you wish to be removed from the register at a later date, you should contact…………………………………………..

You have certain rights under data protection law which are:

- Withdraw your consent, for example if you opted in to be added to a participant register
- Access your personal data or ask for a copy
- Rectify inaccuracies in personal data that we hold about you
- Be forgotten, that is your details to be removed from systems that we use to process your personal data
- Restrict uses of your data
- Object to uses of your data, for example retention after you have withdrawn from a study

Some restrictions apply to the above rights where data is collected and used for research purposes.

You can find out more about your rights on the website of the Information Commissioners Office (ICO) at https://ico.org.uk

You also have a right to complain the ICO if you are unhappy with how your data has been handled. Please contact the University Data Protection Officer in the first instance.

Below information to be added unless covered in other areas of the Information Sheet (see guidance for what needs to be included)

The purposes of the use of personal data (what the study is for)

The categories of personal data that are not obtained directly from the participant (if applicable)

The recipients or categories of recipients of the personal data (to include third parties the data may be shared with, for example, other researcher at HEI's, organisation or job role)

The details of transfers of the personal data to any countries outside the EU including international organisations (if applicable).

The retention periods for the personal data.

The details of the existence of automated decision-making, including profiling (if applicable – more information on whether this would apply to your study can be found here: https://ico.org.uk/for-organisations/guide-to-the-general-data-protection-regulation-gdpr/individual-rights/rights-related-to-automated-decision-making-including-profiling/

Consent Form

1. I have read and had explained to me by **Ozge Saracbasi** the accompanying Information Sheet relating to the project on **"Transferring Skills via Haptic Interaction"**

2. I have had explained to me the purposes of the project and what will be required of me, and any questions I have had have been answered to my satisfaction. I agree to the arrangements described in the Information Sheet in so far as they relate to my participation.

3. I understand that participation is entirely voluntary and that I have the right to withdraw from the project any time, and that this will be without detriment.

4. This project has been subject to ethical review, according to the procedures specified by the University Research Ethics Committee and has been given a favourable ethical opinion for conduct.

5. I have received a copy of this Consent Form and the accompanying Information Sheet.

   Participant ID: ………………………………………………………………………………

   Signed: …………………………………………...………………………………

   Date: ………………………………………………………...………………………

Transferring Skills via Haptic Interaction.

Subject Information

Participant ID:

Age:

Gender: male / female / other / prefer not to say

Handedness: right handed / left handed

Post Experiment Questionnaire

Participant ID:

Please answer the following questions using a scale from 0 to 5 with 0 = strongly disagree and 5 = strongly agree.

1) Do you feel that task was difficult to complete?

0	1	2	3	4	5

2) Do you feel the role of ‘Leader’ and ‘Follower’?

0	1	2	3	4	5

3) Do you feel that the task became easier with each successive trial?

0	1	2	3	4	5

4) Do you feel that you and your partner performed well during the task?

0	1	2	3	4	5

5) Do you feel haptic guidance while ‘Learning Session’?.

0	1	2	3	4	5

ETHICS REVIEW APPLICATION FORM

To be used for School *or* University level review

Please append all relevant and supporting documentation to this project application form when submitting for School level (SREC) or University (UREC) review. Text boxes will expand as required and all language used to explain or justify the application should be comprehensible to a lay person.

Application form and all associated documents should be submitted electronically.

Submission deadline dates for UREC can be found on the UREC webpage.

Section 1: APPLICATION DETAILS

1.1 PROJECT AND DATES				
Title	Transferring Skills via Haptic Interaction			
Date of submission	19/10/2020			
Start date	02/11/2020			
End date	31/12/2021			
1.2 APPLICANT DETAILS				
Chief Investigator	Yoshikatsu Hayashi			
Please note that an undergraduate or postgraduate student cannot be a named Chief Investigator for research ethics purposes. The supervisor must be declared as Chief Investigator.				
Is the project being carried out in whole or in part to support a student degree?				
☒ Yes	☐ Undergraduate	☐ Masters	☒ PhD	
☐ No				
School	University of Reading			
Department	Biological Sciences			
Email	y.hayashi@reading.ac.uk			
Telephone	6701			
All other Applicants	Name:	School	Position	Email
	Ozge Saracbasi	University of Reading	PhD Student	o.o.saracbasi@pgr.reading.ac.uk
	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.

1.3 WHAT REVIEW IS NEEDED?

Please tick the appropriate box below to confirm which review your ethics application requires.

Please tick all that apply.

☒ School Level Review (SREC)	☐ External (for example, HRA)
☐ University Research Ethics Committee Review (UREC)	

Projects expected to require review by the University Research Ethics Committee (for example; research involving NHS patients, research involving potential for distress to participants) must be reviewed by the Chair of the School Ethics Committee or the Head of School before submission to UREC. For further information see Section 16 of the UREC Guidance.

1.4 EXTERNAL RESEARCH ETHICS COMMITTEES

Please provide details of other external research ethics committees from whom a favourable ethics opinion will be required (for example; HRA REC)

Name of Committee	Date of submission / approval	Reference	Status
Click here to enter text.	Click here to enter a date.	Click here to enter text.	Click here to enter text.

1.5 PROJECT SUBMISSION DECLARATION

On behalf of my co-applicants and myself,

- I confirm that to the best of my knowledge I have made known all information relevant to the appropriate Research Ethics Committee and I undertake to inform the Committee(s) of any such information which subsequently becomes available whether before or after the research has begun
- I understand that it is a legal requirement that both staff and students undergo Disclosure and Barring Service checks when in a position of trust (for example; when working with children or vulnerable adults)
- I confirm that if this project is an intervention study, a list of names and contact details of the participants in this project will be compiled and that this, together with a copy of the Consent Form, will be retained within the School for as long as necessary.
- I confirm that I have given due consideration to equality and diversity in the management, design and conduct of the research project.
- (For Chemistry, Food & Pharmacy (CFP) only) I confirm the Internal Review has been undertaken by Click here to enter text. and I have made the changes requested.

SIGNED, CHIEF INVESTIGATOR

06/10/2020

Where required by the School's Research Ethics Procedures, this ethics application should be signed off by the appropriate person to confirm the School Body are content for this application to be reviewed by UREC.

Chemistry, Food & Pharmacy – will require sign off from: Chair of SREC, Head of Department and School Ethics Administrator – insert rows below as required.

SIGNED, AUTHORISING SIGNATORY

Signature:	Position:	Date:
	Choose an item.	Click here to enter a date.

Section 2: PROJECT DETAILS

2.1 LAY SUMMARY

Please provide a summary of the project in plain English that can be understood by a non-specialist audience, which includes a description of the background of the study (existing knowledge), the questions the project will address, the methods to be used and the key ethical issues.

Please note the lay summary should not contain references and be no more than 500 words.

Skill means a learned ability through observation or training. Driving a car, dancing or playing sports can be given as an example of skills. Skill transfer is a method in which the trainer teaches a person how to perform a new task or skill.

Previous research has shown that when two people cooperate with each other to achieve a joint task (a task requiring coordination and cooperation between the partners like carrying a heavy table or dancing tango), they faced dual instabilities arising from the environment (i.e. unknown environment with external nonlinear forces) and interaction with a partner (i.e. the person performing the task together).The study has proven that performing a joint task with an expert (a subject that completed the learning process in previous experiments) leads to the greatest performance compared to a novice (a subject who has no experience). Also, the skills acquired from a joint task can be transferred to an individual performance only if the non-expert subject had prior experience about the dynamics of the task.

In the light of the previous research, we will investigate people how to learn their partner motion for the better motor coordination under a cooperative task. While the previous research has explained the process of learning the environmental dynamics by applying bimanual configuration (performed a task by a person using both hands) and dyadic configuration (performed a task by two people together), this study will examine the process of learning the partner's motion with paired participants by swapping the partners.

In the context of coordination tasks in unknown environments, people need to predict their partner's feedback to control their motion. Haptic robotic interface plays an important role as being the channel for mutual sharing of intentions. The experiment will investigate the process by applying a simple target reaching task performed by participants using a Phantom Haptic Arm (shown the photo of the haptic arm in Figure 1).

Figure 1.Haptic Device (created at BEL Lab)

The experiment will be performed in three days with 20 participants at Brain Embodiment Lab (BEL), in G60, Polly Vacher building. The experimental protocol requires three days considered as respectively baseline, learning and evaluation. The participants will be grouped randomly in the beginning of the experiments. In the first day, participants will be asked to hold the cap of the haptic device created at BEL lab and control the cursor to bring the joint-cursor to randomly placed target. In the second day, the paired participants will be swapped, and they will perform the same task again. In the last day, they perform the same task with their same partner as in the first day. The session can be thought as evaluation. At the end of each experiment, each participant will be asked to answer a post experiment questionnaire designed to collect information about the social aspects of the experiment. Each session of this study will last approximately 40 minutes. During the task, experimenters will record the forces exerted by the participants on the robotic device along with the position, velocity and the resulting acceleration of the robotic devices.

2.2 PRIMARY RESEARCH QUESTION

Please detail the primary research question this project will answer.

How do people learn new skills or adapt to a new person via Haptic Interaction ?

2.3 SECONDARY RESEARCH QUESTION(S)

Please detail any secondary research question(s) this project will answer.

Click here to enter text.

2.4 DESIGN AND PROCEDURE

Please describe concisely what the study will involve, how many times and in what order, for your participants and the procedures and methodology to be used.

Note: Any questionnaires or interview scripts should be appended to this application.

The experiment in which we will investigate the process of learning the partner's motion for the better motor coordination under a cooperative task will include 3 sessions (3 days). Each session will be performed with pairs, and each session includes 4 stages respectively: introduction, familiarization, training and evaluation. For the experiment, we will be collecting data from 20 participants.

Firstly, participants will be grouped as seen in Figure 2 (shown below). It is important that the participants have not met each other before. In the first day (The session of 'Baseline'), participants will perform a reaching task designed with 'MATLAB' software. After the participants perform the experiment in the first day, they will be swapped as seen in the Figure 2. For example, subject A will execute the task with subject D instead of subject B on the day 2. The swapped people will perform the same experiment in the second day (The session of 'Learning') so that the effects of the presence of another person in learning process will be explained. The other session is 'Evaluation'. In this session, the pairs in the first day will be employed again to evaluate their individual adaptabilities. In the three sessions the aim will be clarifying the difference of adaptability between the groups. The payment for the participation will be made if the participant attends all three sections to prevent partner's unavailability in later sessions.

Day - 1	Day - 2	Day - 3
A-B	A-D	A-B
C-D	C-B	C-D
E-F	E-H	E-F
G-H	G-F	G-H
I-J	I-L	I-J
K-L	K-J	K-L
M-N	M-P	M-N
O-P	O-N	O-P
R-S	R-U	R-S
T-U	T-S	T-U

Figure 2. The Participant Groups

As mentioned before, each session includes 4 stages respectively: introduction, familiarization, training and evaluation. (The stages can be seen with details below in Figure 3.) Each stage will be performed as a pair. The screen of this study will be seen in Figure 4. In each stage, the participants will see the same screen as shown in Figure 4 to see the position of their own haptic device, partner's haptic device and target.

Figure 3. Stages of the Experiment

1st Stage: Introduction to the participants (5 minutes)

In this stage, participants will be informed about the experiment. The details of the experiment such as how to perform the experiment will be explained to the participants.

2nd Stage: Familiarization (5 minutes)

Participants will try to bring the object to the target position before the experiment by using the instructions given in the stage of 'Introduction', so that they can familiarize with the study.

3rd Stage: Training Period (20 minutes)

Participants will perform the study with their pairs by using the haptic device created at the BEL Lab. Four different conditions will be performed and tested in this experiment corresponding to a different number of targets on the screen respectively one target, two targets, five targets and ten targets in the same order in every session. Each condition is repeated ten times. In total, each experiment consists of 40 trials, and each trial lasts 40 seconds. One-minute rest periods are given after every ten trials.

This experiment includes a type of cooperative task. In the cooperative tasks, increasing the number of the targets could lead to confusion. Also, the experiment needs coordination between the people so that they can predict their partner's feedback to control their motion. This experiment will apply haptic robotic interface for a channel to share intentions. In other words, the aim to select a different number of targets will be testing the haptic interface.

4th Stage: Evaluation Period (10 minutes)

The participants will be asked to fill in a questionnaire aimed at understanding each participant's impressions during the experiment at the end of the experiment.

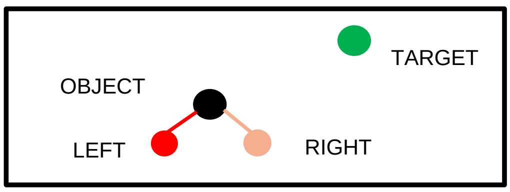

Figure 4. The screen of the study

As mentioned before, the participants will sit in separate rooms. In the Figure 4, left refers to the left cursor (the robotic device in the left room), and right refers to the right cursor (the robotic device in the right room). Object means the joint-cursor which will be connected to the left cursor and right cursor with the virtual springs. The aim in this study is to control the cursor to bring the joint-cursor to randomly placed target (shown as a green circle in Figure 4).

Also, during the task, experimenters will record the forces exerted by participants on the robotic device along with the position, velocity and the resulting acceleration of the robotic devices. The time and position values in three days will be compared by ANOVA statistical test. It is important that the consent and information forms will be given to the participants prior to enrolling on the study.

2.5 LOCATION

Please describe where the research will take place.

The experiment will take place in the Brain Embodiment Lab (BEL) located in G60, Polly Vacher building. There is a comfortable seating for the participant, the ambient lighting is proper, and monitors are kept at safe distance to avoid stress on eyes. Enough breaks will be given to the participants. There are no major risks associated with the experiment. The experiment operator will be present with the participant at all times.

Please state whether an appropriate risk assessment/ local review has been undertaken.

☒ Yes (The H&S measures or guidance for covid19)
☐ No
☐ Not required

Notes:
- Ensure specific risk assessments have been undertaken for non-University locations (for example; schools or participant homes). Please consult either your School Ethics Contact or UREC for guidance.
- If the project is to take place in Hugh Sinclair Unit of Human Nutrition, it must be reviewed and approved by the Hugh Sinclair Manager.

2.6 FUNDING

Is the research supported by funding from a research council or other external source (for example; charities, businesses)?

☒ Yes
☐ No

If "yes", please,

(a) Give details of the funding body;

Ministry of Education, Turkish Republic.

(b) Confirm if the funder specifically stipulates review by the University Research Ethics Committee.

☐ Yes
☒ No

2.7 ETHICAL ISSUES

Please summarise the main ethical issues, including harms and risks, arising from your study and explain how you have addressed them.

There are no ethical issues, apart from matters related to data storage, usage and confidentiality – these are discussed in Sections 2.8 and 2.9."

2.8 DECEPTION

Will the research involve any element of intentional deception (for example; providing false or misleading information about the study)?

☐ Yes
☒ No

If "yes", please justify and append a description of the debriefing procedure.

Click here to enter text.

2.9 PAYMENT

Will research participants receive any payments, reimbursement of expenses or any other benefits or incentives for taking part in this research?

☒ Yes
☐ No

If "yes", please specify and justify the amount.

£10 per each session (in total £30)

2.10 DATA PROTECTION

What steps will be taken to ensure appropriate secure handling of personal data? Give comprehensive details on the collection, retention, sharing and disposal of participant personal data.

Personal data means any data relating to a participant who could potentially be identified. It includes pseudonymised data capable of being linked to a participant through a unique code number.

For guidance on data protection please, see the Data Protection for Researchers Guidance document.

Data collected in this experiment is of two categories- 1) Digital: Kinematic and Haptic data. 2) Hard copy: questionnaire.

1) Digital data storage and confidentiality

a. *Kinematic and Haptic data:* Kinematic and haptic data will be stored using the pseudonymous user ID. The files will be stored in the secure shared BEL drive detailed above indefinitely, accessible to members of the research team.

2) Hard copy of questionnaire:

a. *Questionnaire:* Questionnaire asks for age, gender and handedness of the participants. The questionnaire is also targeted at determining the level of cooperation between participants. The aggregate of this information is required for publishing the scientific results of this study. Questionnaire itself will not be shared with anybody. Questionnaires will be anonymised with the unique identifier of the participant just like kinematic data. Questionnaires will be stored securely in BEL in a locked cabinet dedicated for this purpose, separate from the cabinet for consent forms.

Will the research involve any activity that requires a Data Protection Impact Assessment (DPIA)?

☐ Yes
☒ No

If "yes", please append the "DPIA Appendix A – Screening Questions".

2.11 INFORMED CONSENT

a. Will you obtain informed consent from, or on behalf of, research participants?

☒ Yes (go to question b)
☐ No (go to question c)

b. If "yes", please describe the process by which they will be informed about the nature of the study and the process by which you will obtain consent.

c. If "no", you are not obtaining consent, please explain why (for example; 'opt-out' methodology without the acquisition of consent)?

Please append all relevant participant facing information documentation for participants, parents or guardians. Please note, age-appropriate information sheets must be supplied for all participants wherever possible, including children. Assent should be obtained from children, under 16 years, in addition to the consent required from parents, guardians or carers.

Written information sheet outlining the experiment procedure will be presented to the participant. Experiment would be explained to the participant by the researcher and then the written consent would be obtained from the participants by completing the consent form at the beginning of the experiment. Participants reserve the right to withdraw from the experiment at any time without giving any reason.

The consent form is the only document that will contain the participant's name. Signed consent forms will be stored securely in the locked cabinet storage facility in BEL dedicated for this purpose. Consent forms will not be shared with the third parties.

The consent forms will be stored for 5 years after completion of the PhD, and then destroyed securely.

2.12 GENOTYPING

Are you intending to genotype the participants?

☐ Yes
☒ No

If "yes", which genotypes will be determined?

Click here to enter text.

Section 3: PARTICIPANT DETAILS

3.1 PARTICIPANT NUMBER

How many participants do you plan to recruit?

Please briefly explain why the number is appropriate to answer the study's research question(s).

Needed 20 Participants

3.2 PARTICIPANT CHARACTERISATION

What age-range of participants will you recruit?

18 years old or older

Please list the principal inclusion and exclusion criteria.

- Have normal or corrected to normal vision
- Do not have any motor or communication impairing disabilities and,
- Are not taking any medications affecting brain chemistry.

Click here to enter text.

3.3 RECRUITMENT

Please describe the recruitment process and append any advertising if used.

3.4 NHS AND SOCIAL SERVICES INVOLVEMENT
Will participants be recruited because of their status as NHS patients or Social Services clients, or identified through those services' records? ☐ Yes ☒ No If "yes", please give details of current status of the HRA REC review.
Click here to enter text.
Will the study involve adult participants unable to consent for themselves as defined by the Mental Capacity Act 2005 or other vulnerable adults? ☐ Yes ☒ No If "yes", please detail the associated procedures as set out in the HRA REC application.
Click here to enter text.

CHECKLIST

1. The Application form has the appropriate signatories	Yes
2.The Participant Information Sheet includes a statement to the effect that the project has been reviewed by the appropriate Research Ethics Committee and has been given a favourable ethical opinion for conduct.	Yes
3. The Participant Information Sheet contains the relevant Data Protection information.	Yes

4. EITHER	a) The proposed research will not generate any information about the health of participants;	☒
OR	b) If the research could reveal adverse information regarding the health of participants, their consent to pass information on to their GP will be included in the consent form and in this circumstance I will inform the participant and their GP, providing a copy of the relevant details to each and identifying by date of birth.	☐
OR	c) I have explained within the application why (b) above is not appropriate.	☐
5. EITHER	a) The proposed research does not involve children under the age of 5;	☒
OR	b) My Head of School (or authorised responsible person) has given details of the proposed research to the University's insurance officer.	☐
6. EITHER	a) The proposed research does not involve the taking of blood samples:	☒
OR	b) For anyone whose proximity to the blood samples brings a risk of Hepatitis B, documentary evidence of immunity prior to the risk of exposure will be retained by the Head of School or authorised responsible person.	☐
7. EITHER	a) The proposed research does not involve the storage of human tissue, as defined by the Human Tissue Act 2004;	☒
OR	b) I have explained within the application how the requirements of the Human Tissue Act 2004 will be met.	☐
8. EITHER	a) The proposed research does not involve the use of ionising radiation;	☒

OR	b) I am aware the proposed research will require HRA REC review.	☐

VERSION CONTROL

VERSION	KEEPER	REVIEWED	APPROVED BY	APPROVAL DATE
1.0	UREC	Annually	UREC	Sept 18

Researcher (principal): Dr Yoshikatsu Hayashi
Email: y.hayashi@reading.ac.uk
Phone: +44 (0) 118 378 6701

Researcher (role): Ozge Saracbasi (PhD Candidate)
Email: o.o.saracbasi@pgr.reading.ac.uk

School of Biological Sciences
Biomedical Engineering Section
University of Reading
Reading RG6 6DH

Phone: +44 (0) 118 378 8072
email: biosciences@reading.ac.uk

INFORMATION SHEET

Project Title: Transferring Skills via Haptic Interaction

Why are we doing this study?

People can perceive the reactions of the people in their surroundings via visual, verbal and haptic interaction and respond to them. Previous research (Avila Mireles et al., 2017, 'Skill learning and skill transfer mediated by cooperative haptic interaction') examined the process of learning the dynamics of the environment for better motor coordination under a cooperative task. We will investigate how people learn a partner's motion for better motor coordination under a cooperative task. While previous research has explained the process of learning the environmental dynamics by applying bimanual (a person performing a task using both hands) and dyadic (two people performing a task together) configurations, this study will examine the process of learning the partner's motion with paired participants by swapping the partners.

What is the purpose of the study?

We will investigate the process of learning the partner's motion for better motor coordination under a cooperative task with paired participants. The experiment will be performed over three days with 20 participants. The study aims to understand how people learn their partner's motion in a cooperative task through use of a robotic device. The robotic device can be thought of as a way to share people's intentions with each other. With the help of this study, we will evaluate people's individual adaptabilities in a joint task.

Who is eligible to participate in the study?

We are looking for healthy volunteers who

- Are 18 years old or older
- Have normal or corrected to normal vision
- Do not have any motor or communication impairing disabilities and,
- Are not taking any medications affecting brain chemistry.

How can you get involved?

If you would like to participate, please email Ozge Saracbasi at o.o.saracbasi@pgr.reading.ac.uk.

Do I have to take part?

Participation is entirely voluntary, and you can withdraw at any time without giving a reason, and this will be without detriment.

What will be involved if you take part?

The experiment involves three sessions over three days, when you will be asked to perform tasks with a partner who will be randomly chosen and assigned to work with you. Each session of the experiment lasts approximately 40 minutes. In all sessions, participants will be asked to hold the tip of a robotic device created in our lab and, together with their partner, move a cursor to a randomly placed target on the computer screen. The robotic device can be thought as a way to share people's intentions with each other. The robotic devices used by two participants will be connected with virtual springs. That is to say, the participants' movements will affect and be affected by their partner's movements through this robotic device and virtual spring. Four different conditions will be performed and tested in this experiment corresponding to a different number of targets on the screen (one target, two targets, five targets and ten targets). Each condition is repeated ten times. In total, each experiment consists of 40 trials, and each trial lasts 40 seconds. One-minute rest periods are given after every ten trials. We will record the forces exerted by participants on the robotic device, along with the acceleration, position and velocity of the robotic devices during the experiment. We will also request that you fill in a brief questionnaire after you have completed the trials.

Prior to starting the experiment, you will be asked to provide written informed consent and to complete a questionnaire about your gender, date of birth and handedness.

Confidentiality, storage and disposal of information

You will be asked to provide your name and to sign a consent form so that we can keep a record of your participation in the study, however, this information will be kept confidential and will not be disclosed publicly. The consent form will be stored in a locked filing cabinet in our lab, and destroyed securely 5 years after completion of the project.

All data from the study will be stored, processed, and reported using a pseudonymous user ID. It will be reported only as a part of an aggregate dataset collected from multiple participants. Hardcopies of the questionnaire will be transcribed into electronic form, and the hardcopies stored in a locked filing cabinet in our lab, separate from the consent forms, and destroyed 5 years after completion of the project. The questionnaire data will be used to understand the relationships that emerge between you and your study partner and will not be used to identify you in any way.

Pseudonymised haptic data will be stored securely and password protected on the internal Brain Embodiment Lab server provided by the university, accessible to members of the research team now and in the future.

Are there any benefits/risks to taking part [e.g. health]?

There are no benefits or health risks to taking part in this experiment. However, you might feel fatigue because of the movement repetition involved in reaching a target.

What will the results of the study be used for?

The results of this study will contribute towards PhD research and scientific publications. If you would like to learn the results at the end of the study, please contact the researchers.

What payment will be made for participation in the study?

You will be remunerated for your time and participation with £10 per each session (£30 in total).

Where will the studies take place?

The study will take place in the Brain Embodiment Lab, Biomedical Engineering, located in the Polly Vacher building on the University of Reading's Whiteknights campus. A researcher will contact you to provide further directions, and to arrange a time slot for you.

Who has reviewed the study?

This project has been subject to ethical review, according to the procedures specified by the University Research Ethics Committee and has been given a favourable ethical opinion for conduct.

Contact details for further questions:

Experiments and the research will be conducted by Ozge Saracbasi (o.o.saracbasi@pgr.reading.ac.uk) who is currently a 3rd year PhD researcher in Biomedical Engineering.

Ozge is supervised by Dr Yoshikatsu Hayashi and Prof William Harwin.
Contact details: PI Name: Yoshikatsu Hayashi
Email: y.hayashi@reading.ac.uk Phone: +44 (0) 118 378 5024

In the event of a complaint

If you have any comments or if you have a complaint, you can contact the Chair of the Ethics Committee of the School of Biological Sciences, Dr M. Alejandra Perotti Email: m.a.perotti@reading.ac.uk

Thank you for your help.

Investigator Contact Details:

Dr. Yoshikatsu Hayashi	Ozge Saracbasi
e: y.hayashi@reading.ac.uk	e: o.o.saracbasi@pgr.reading.ac.uk

Appendix C: data protection for information sheets

The organisation responsible for protection of your personal information is the University of Reading (the Data Controller). Queries regarding data protection and your rights should be directed to the University Data Protection Officer at imps@reading.ac.uk, or in writing to: Information Management & Policy Services, University of Reading, Whiteknights, P O Box 217, Reading, RG6 6AH.

The University of Reading collects, analyses, uses, shares and retains personal data for the purposes of research in the public interest. Under data protection law we are required to inform you that this use of the personal data we may hold about you is on the lawful basis of being a public task in the public interest. If you withdraw from a research study, which processes your personal data, dependant on the stage of withdrawal, we may still rely on this lawful basis to continue using your data if your withdrawal would be of significant detriment to the research study aims. We will always have in place appropriate safeguards to protect your personal data.

If we have included any additional requests for use of your data, for example adding you to a registration list for the purposes of inviting you to take part in future studies, this will be done only with your consent where you have provided it to us and should you wish to be removed from the register at a later date, you should contact Ozge Saracbasi (o.o.saracbasi@pgr.reading.ac.uk).

You have certain rights under data protection law which are:

- Withdraw your consent, for example if you opted in to be added to a participant register
- Access your personal data or ask for a copy
- Rectify inaccuracies in personal data that we hold about you
- Be forgotten, that is your details to be removed from systems that we use to process your personal data
- Restrict uses of your data
- Object to uses of your data, for example retention after you have withdrawn from a study

Some restrictions apply to the above rights where data is collected and used for research purposes. You can find out more about your rights on the website of the Information Commissioners Office (ICO) at https://ico.org.uk

You also have a right to complain the ICO if you are unhappy with how your data has been handled. Please contact the University Data Protection Officer in the first instance.

APPENDIX B: SAMPLE CONSENT FORM

Consent Form

Please use tick box after each statement to confirm it has been read and agreed to.

1. I have read and had explained to me by … **Ozge Saracbasi** … the accompanying Information Sheet relating to the project on: …**"Transferring Skills via Haptic Interaction"**…

2. I have had explained to me the purposes of the project and what will be required of me, and any questions I have had have been answered to my satisfaction. I agree to the arrangements described in the Information Sheet in so far as they relate to my participation. ☐

3. I have had explained to me what information will be collected about me, what it will be used for, who it may be shared with, how it will be kept safe, and my rights in relation to my data. ☐

4. I understand that participation is entirely voluntary and that I have the right to withdraw from the project any time, and that this will be without detriment. ☐

5. I understand that the data collected from me in this study will be preserved, and subject to safeguards will be made available to other authenticated researchers. ☐ *****

6. This project has been reviewed by the University Research Ethics Committee and National Research Ethics committee where relevant, and has been given a favourable ethical opinion for conduct.

7. I have received a copy of this Consent Form and of the accompanying Information Sheet. ☐

Name: …………………………………………………………………………………

Signed: …………………………………………...………………………………

Date: ……………………………………………………...………………………

I am happy to be included on a register of research participants for the purposes of being contacted about further studies by…… **Ozge Saracbasi** …….. Please tick ☐ (optional)

University of Reading

Subject Information

Participant ID:

Age:

Gender: male / female / other / prefer not to say

Handedness: right handed / left handed

Post Experiment Questionnaire

Participant ID:

Please answer the following questions using a scale from 0 to 5 with 0 = strongly disagree and 5 = strongly agree.

1) I felt the task was difficult to complete.

0	1	2	3	4	5

2) I felt the task is performed cooperatively.

0	1	2	3	4	5

3) I felt that the task became easier with successive trials.

0	1	2	3	4	5

4) I felt that my partner and I performed well during the task.

0	1	2	3	4	5

5) I was able to feel haptic guidance during the ‘Learning Session’ which is performed in the second day of the experiment.

0	1	2	3	4	5

ETHICS REVIEW APPLICATION FORM

To be used for School *or* University level review

Please append all relevant and supporting documentation to this project application form when submitting for School level (SREC) or University (UREC) review. Text boxes will expand as required and all language used to explain or justify the application should be comprehensible to a lay person.

Application form and all associated documents should be submitted electronically.

Submission deadline dates for UREC can be found on the UREC webpage.

Section 1: APPLICATION DETAILS

1.1 PROJECT AND DATES	
Title	Neural Correlates of Haptic Interaction in a cooperative task
Date of submission	04/06/2021
Start date	12/07/2021
End date	31/07/2022
1.2 APPLICANT DETAILS	
Chief Investigator	Yoshikatsu Hayashi

Please note that an undergraduate or postgraduate student cannot be a named Chief Investigator for research ethics purposes. The supervisor must be declared as Chief Investigator.

Is the project being carried out in whole or in part to support a student degree?

☒ Yes ☐ Undergraduate ☐ Masters ☒ PhD

☐ No

School	University of Reading
Department	Biological Sciences
Email	y.hayashi@reading.ac.uk
Telephone	6701

All other Applicants	Name:	School	Position	Email
	Ozge Saracbasi	University of Reading	PhD Student	o.o.saracbasi@pgr.reading.ac.uk
	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.

1.3 WHAT REVIEW IS NEEDED?

Please tick the appropriate box below to confirm which review your ethics application requires.

Please tick all that apply.

☒ School Level Review (SREC)	☐ External (for example, HRA)
☐ University Research Ethics Committee Review (UREC)	

Projects expected to require review by the University Research Ethics Committee (for example; research involving NHS patients, research involving potential for distress to participants) must be reviewed by the Chair of the School Ethics Committee or the Head of School before submission to UREC. For further information see Section 16 of the UREC Guidance.

1.4 EXTERNAL RESEARCH ETHICS COMMITTEES

Please provide details of other external research ethics committees from whom a favourable ethics opinion will be required (for example; HRA REC)

Name of Committee	Date of submission / approval	Reference	Status
Click here to enter text.	Click here to enter a date.	Click here to enter text.	Click here to enter text.

1.5 PROJECT SUBMISSION DECLARATION

On behalf of my co-applicants and myself,

- I confirm that to the best of my knowledge I have made known all information relevant to the appropriate Research Ethics Committee and I undertake to inform the Committee(s) of any such information which subsequently becomes available whether before or after the research has begun
- I understand that it is a legal requirement that both staff and students undergo Disclosure and Barring Service checks when in a position of trust (for example; when working with children or vulnerable adults)
- I confirm that if this project is an intervention study, a list of names and contact details of the participants in this project will be compiled and that this, together with a copy of the Consent Form, will be retained within the School for as long as necessary.
- I confirm that I have given due consideration to equality and diversity in the management, design and conduct of the research project.
- (For Chemistry, Food & Pharmacy (CFP) only) I confirm the Internal Review has been undertaken by Click here to enter text. and I have made the changes requested.

SIGNED, CHIEF INVESTIGATOR

01/06/2021

Where required by the School's Research Ethics Procedures, this ethics application should be signed off by the appropriate person to confirm the School Body are content for this application to be reviewed by UREC.

Chemistry, Food & Pharmacy – will require sign off from: Chair of SREC, Head of Department and School Ethics Administrator – insert rows below as required.

SIGNED, AUTHORISING SIGNATORY

Signature:	Position:	Date:
	Choose an item.	Click here to enter a date.

Section 2: PROJECT DETAILS

2.1 LAY SUMMARY

Please provide a summary of the project in plain English that can be understood by a non-specialist audience, which includes a description of the background of the study (existing knowledge), the questions the project will address, the methods to be used and the key ethical issues.

Please note the lay summary should not contain references and be no more than 500 words.

Humans need to learn new skills throughout their life to use in daily life activities (e.g. driving) or art performances (e.g. playing musical instruments). Skill means a learned ability through observation or training. Recent study suggests that when two people cooperate with each other to achieve a joint task (a task requiring coordination and cooperation between the partners like dancing tango), they face dual instabilities arising from the environment (i.e. unknown environment with external nonlinear forces) and interaction with a partner (i.e. the person performing the task together).

In the previous study, we investigated the dual instability problem by identifying the behavioural correlates, and we demonstrated that if humans firstly familiarize with their partners and learn their partner's dynamics, they can learn environmental dynamics together. Step-by-step learning through separation of the dynamics in the learning environment result in mutual skill learning (learning through the interaction with a person who have same skill level). However, it is unclear 'How the electrical brain activity may change while mutual motor learning'.

In addition, it is known that mutual behavioural negotiation or mutual adaptation results in interactional synchrony (synchrony between partners). We hypothesize that mutual motor learning which is a result of mutual adaptation would lead to interbrain synchronization between interacting subjects. Here, we aim to explore the functional brain network affected from the interaction with a partner under unknown external force field. Identifying the neural correlates of skill learning through the interaction with a partner may guide to explain the dual instability problem.

The use of electroencephalography (EEG), which can measure electrical brain activity, may be able to explain the changes in brain dynamics induced by motor skill learning. Therefore, to investigate interbrain synchronization, in this study, electroencephalogram (EEG) hyperscanning technology will be used. Here, hyperscanning means the recording of neural signals from more than one individual simultaneously. EEG coherence analyses will help to characterize the functional network during mutual skill learning.

In this study we will investigate the changes in neural connectivity both within each participant's brain and between participants of the same dyad while performing a cooperative task using haptic robotic interface under the external force field. In the context of cooperative tasks in unknown environments, people need to predict their partner's feedback to control their motion. Haptic robotic interface plays an important role as being the channel for mutual sharing of intentions. In this study a Phantom Haptic Arm (Figure 1) will be used as a haptic robotic interface.

Figure 1.Haptic Device (created at BEL Lab)

This study will be performed with 20 participants at Brain Embodiment Lab (BEL), in G60, Polly Vacher building. The participants will be grouped randomly in the beginning of the experiments.

In the experiment participants will be asked to hold the cap of the haptic device created at BEL lab and control the cursor to bring the joint-cursor to randomly placed target with their preassigned partner who sit in the separate room. The experiment will last approximately two hours, including the time necessary to prepare each participant for EEG set up (20-min) and remove them(10-min). At the end of the experiment, each participant will be asked to answer a post experiment questionnaire designed to collect information about the social aspects of the experiment.

During the task, experimenters will record the forces exerted by the participants on the robotic device along with the position, velocity and the resulting acceleration of the robotic devices as well as the EEG data obtained from 32 channels.

2.2 PRIMARY RESEARCH QUESTION

Please detail the primary research question this project will answer.

How is the functional brain network affected from the interaction with a partner through haptic interaction under unknown force field ?

2.3 SECONDARY RESEARCH QUESTION(S)

Please detail any secondary research question(s) this project will answer.

Click here to enter text.

2.4 DESIGN AND PROCEDURE

Please describe concisely what the study will involve, how many times and in what order, for your participants and the procedures and methodology to be used.

Note: Any questionnaires or interview scripts should be appended to this application.

In this study electroencephalogram (EEG) hyperscanning technology will be used to investigate neural correlation both within each participant's brain and between participants while performing a cooperative task. This study will consist of EEG experiments on healthy human participants without any motor impairments. To record EEG related to social cooperation between pairs, 32 non-invasive gel based EEG electrodes will be placed on the participant's scalp. (see Figure 2 for the electrode positions)

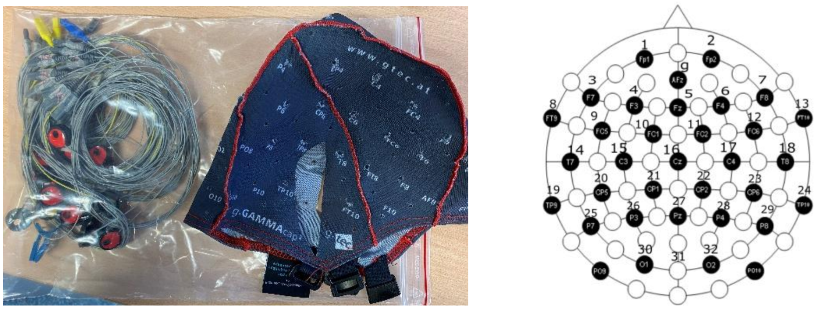

Figure 2. The EEG cap and the locations of the 32 EEG channels

The participants will perform a reaching task designed with 'MATLAB' software. Within the task the participants with EEG cap will be asked to hold the cap of haptic device and bring a joint-cursor (black circle) to randomly placed target (green circle) with their pre-assigned partner.

As seen in the Figure 3.a, the joint cursor (black circle) is connected to two cursors (red and purple circle) controlled by the paired subjects with virtual springs (red and purple line) and subject to external force field. This study aims to find the neural correlates of the participants interacted with haptic feedback. Thus, during the experiment the position of the left and right cursors controlled by the paired subjects and virtual springs will be invisible and the joint cursor will be visible on display as seen in the Figure 3.b.

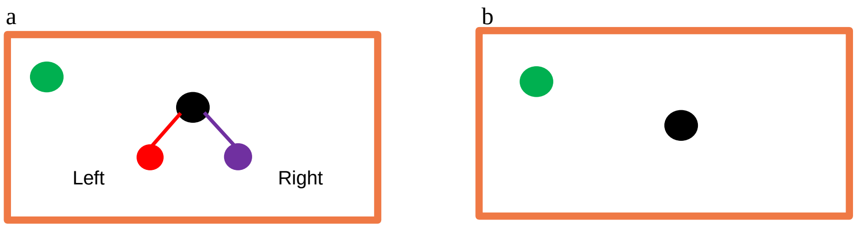

Figure 3. The screen of the study

The experiment will be performed by 20 participants in total. This study aims to find how the functional brain network is affected from the interaction with the partner through haptic interaction under the unknown external force field. To understand the change in neural networks depending on the presence of the external force field while performing the task with a partner, the experiment will be performed in two different types. As seen in the Figure 4 , in the 1st group the external force field is off (training phase without external force field), and then on (training phase with external force field) whereas in the second group the external force field is on first and then off. The participants will be assigned to one of these two groups, and each group will include 10 participants. The difference of these groups will be the order of applying the external force field in a cooperative task.

Group - 1

Familiarization **(P1-P2)**	**Training without** **External Force Field** **(P1-P2)**	**Break**	**Training with** **External Force Field** **(P1-P2)**	**Wash Out** **(P1-P2)**
1 TS (8 Trials)	12 TS (96 Trials)	15-minute	12 TS (96 Trials)	1 TS (8 Trials)

Group - 2

Familiarization (P1-P2)	Training with External Force Field (P1-P2)	Break	Training without External Force Field (P1-P2)	Wash Out (P1-P2)
1 TS (8 Trials)	12 TS (96 Trials)	15-minute	12 TS (96 Trials)	1 TS (8 Trials)

Figure 4. Experimental Protocol

As seen in the Figure 4, the experimental protocol was set as in 4 phases with 15-minute break. In each phase, the participants will see the same screen as shown in Figure 3.b to see the position of joint cursor and target simultaneously and interact with their partner through haptic feedback.

The experiment will be performed in two groups in which each group will perform 4 phases respectively: familiarization, training and wash out.

The experiment will be performed as a pair and the participants will sit in separate rooms. Firstly, the participants will be informed about the experiment. The details of the experiment such as how to perform the experiment will be explained to the participants. After the instructions, the next step will be gelling the participants up, and then checking the EEG signals. We will use an abrasive electrolyte gel (similar in action to a cosmetic exfoliating scrub) and 70% isopropyl alcohol in order to clean the surface of the scalp at points of contact with the electrodes to improve the electrical contact with the skin. When the participants are ready to perform the task with EEG caps, the experimental phases will be started as seen in the Figure 4.

1st Phase: Familiarization Phase (5 minutes)

Participants will try to bring the object to the target position by using the instructions given in the stage of 'Introduction', so that they can familiarize with the study.

2nd & 3rd Phase: Training Phase (2 x 25 minutes)

There are two Training phases: one with external force field and one is without. In the 1st group the external force field is off (training phase without external force field), and then on (training phase with external force field) whereas in the second group the external force field is on first and then off. Also there will be a rest time as 15-minute between the 2nd and 3rd phases. Each training phase consists of 12 target sets (TS) including 8 trials. In the training phase in all trials, the participants will be asked to move a joint cursor from a home position to randomly placed target as quickly as possible by controlling the robotic arm created at the BEL Lab with their partner. The target will be appeared at one of eight locations equally spaced at 45 degree on a circle around the home position of the joint cursor in each trial.

The experiment needs coordination between the people so that they can predict their partner's feedback to control their motion. This experiment will apply haptic robotic interface for a channel to share intentions.

4th Phase: Wash Out (5 minutes)

Participants will be asked to perform the same task to erase the learned motor skills (i.e. internal model of the partner).

At the end of the experiment, the participants will be asked to fill in a questionnaire aimed at understanding each participant's impressions during the experiment and the EEG caps will be removed. Also, the participants can wash their hair to remove the gel from the hair. We have a hair washing sink with handheld shower and hot water in the lab. We also provide a towel, shampoo and hair dryer.

The EEG signals recorded in the cooperative task will be analysed offline by using MATLAB and EEGLab. Firstly, the data will be bandpass filtered between 0.5 and 40 Hz. After Band-pass filter, ICA (Independent Component Analysis) will be used to find the independent components to remove noise from the data.

In the previous studies coordinated behaviour was identified in the delta (2-3 Hz) and theta (5-7 Hz) frequency bands while playing guitar, and in the phi complex (9.2 – 11.5 Hz) during visually mediated social interactions such that phi 1 increased during uncoordinated movement, and phi 2 increased during coordinated movement.

In the light of previous studies, after removing the noise, the data will be bandpass filtered between 2 and 30 Hz, and the Hilbert transform will be applied to extract the instantaneous phase. The circular correlation coefficient will be used to calculate the synchronization between electrode pairs for all participants and all conditions and also the distribution of the correlations will be created. If the channels are unrelated, the correlation coefficient will be zero. The experimenters will also record the forces exerted by participants on the robotic device along with the position, velocity and the resulting acceleration of the robotic devices. The time and position values will be compared by ANOVA statistical test.

It is important that the consent and information forms will be given to the participants prior to enrolling on the study.

2.5 LOCATION

Please describe where the research will take place.

The experiment will take place in the Brain Embodiment Lab (BEL) located in G60, Polly Vacher building. The EEG recording rooms are well equipped for performing EEG based experiments with human participants and have passed the health, safety and risk analysis. Due precautions will be taken for the safety of the participants as well as the researchers such as – securing the connector cables to avoid tripping, measuring head size to avoid any discomfort while putting the EEG cap on participant. Also, there is a comfortable seating for the participant, the ambient lighting is proper, and monitors are kept at safe distance to avoid stress on eyes. Enough breaks will be given to the participants. There are no major risks associated with the experiment. The experiment operator will be present with the participant at all times.

Please state whether an appropriate risk assessment/ local review has been undertaken.

☒ Yes (the H&S measures or guidance for Covid 19)
☐ No
☐ Not required

Notes:
- Ensure specific risk assessments have been undertaken for non-University locations (for example; schools or participant homes). Please consult either your School Ethics Contact or UREC for guidance.
- If the project is to take place in Hugh Sinclair Unit of Human Nutrition, it must be reviewed and approved by the Hugh Sinclair Manager.

2.6 FUNDING

Is the research supported by funding from a research council or other external source (for example; charities, businesses)?

☒ Yes
☐ No

If "yes", please,

(a) Give details of the funding body;

Ministry of Education, Turkish Republic.

(b) Confirm if the funder specifically stipulates review by the University Research Ethics Committee.

☐ Yes
☒ No

2.7 ETHICAL ISSUES

Please summarise the main ethical issues, including harms and risks, arising from your study and explain how you have addressed them.

There are no ethical issues, apart from matters related to data storage, usage and confidentiality – these are discussed in Sections 2.8 and 2.9.”

2.8 DECEPTION

Will the research involve any element of intentional deception (for example; providing false or misleading information about the study)?

☐ Yes
☒ No

If “yes”, please justify and append a description of the debriefing procedure.

Click here to enter text.

2.9 PAYMENT

Will research participants receive any payments, reimbursement of expenses or any other benefits or incentives for taking part in this research?

☒ Yes
☐ No

If “yes”, please specify and justify the amount.

The experiment lasts 2 hours. £10 per each hour (in total £20)

2.10 DATA PROTECTION

What steps will be taken to ensure appropriate secure handling of personal data? Give comprehensive details on the collection, retention, sharing and disposal of participant personal data.

Personal data means any data relating to a participant who could potentially be identified. It includes pseudonymised data capable of being linked to a participant through a unique code number.

For guidance on data protection please, see the Data Protection for Researchers Guidance document.

Data collected in this experiment is of two categories- 1) Digital: Kinematic and Haptic data. 2) Hard copy: questionnaire.

1) Digital data storage and confidentiality

a. *Kinematic and Haptic data:* Kinematic and haptic data will be stored using the pseudonymous user ID. The files will be stored in the secure shared BEL drive detailed above indefinitely, accessible to members of the research team.

b. *EEG data:* The EEG data recorded from the experiment will be pseudonymised. Each participant will be assigned an pseudonymous user ID, and all electronic data from the study will be stored, processed, and reported using this pseudonymous user ID. This dataset will be stored on a secure shared drive for BEL located on the internal University server, accessible to members of the research team now and in the future. This internal server is managed by central IT and access is available only to the BEL researchers approved for access. Participants cannot be identified by their EEG data which is purely numeric in nature. There is no confidential information in EEG data.

   These pseudonymous data will be stored indefinitely. The data may also be made publicly available via a research data repository, where this is a requirement for a journal, for example.

2) Hard copy of questionnaire:

a. *Questionnaire:* Questionnaire asks for age, gender and handedness of the participants. The questionnaire is also targeted at determining the level of cooperation between participants. The aggregate of this information is required for publishing the scientific results of this study. Questionnaire itself will not be shared with anybody. Questionnaires will be anonymised with the unique identifier of the participant just like kinematic data. Questionnaires will be stored securely in BEL in a locked cabinet dedicated for this purpose, separate from the cabinet for consent forms.

Will the research involve any activity that requires a Data Protection Impact Assessment (DPIA)?

☐ Yes
☒ No

If "yes", please append the "DPIA Appendix A – Screening Questions".

2.11 INFORMED CONSENT

a. Will you obtain informed consent from, or on behalf of, research participants?

☒ Yes (go to question b)
☐ No (go to question c)

b. If "yes", please describe the process by which they will be informed about the nature of the study and the process by which you will obtain consent.

c. If "no", you are not obtaining consent, please explain why (for example; 'opt-out' methodology without the acquisition of consent)?

Please append all relevant participant facing information documentation for participants, parents or guardians. Please note, age-appropriate information sheets must be supplied for all participants wherever possible, including children. Assent should be obtained from children, under 16 years, in addition to the consent required from parents, guardians or carers.

Written information sheet outlining the experiment procedure will be presented to the participant. Experiment would be explained to the participant by the researcher and then the written consent would be obtained from the participants by completing the consent form at the beginning of the experiment. Participants reserve the right to withdraw from the experiment at any time without giving any reason.

The consent form is the only document that will contain the participant's name. Signed consent forms will be stored securely in the locked cabinet storage facility in BEL dedicated for this purpose. Consent forms will not be shared with the third parties.

The consent forms will be stored for 5 years after completion of the PhD, and then destroyed securely.

2.12 GENOTYPING

Are you intending to genotype the participants?

☐ Yes
☒ No

If "yes", which genotypes will be determined?

Click here to enter text.

Section 3: PARTICIPANT DETAILS

3.1 PARTICIPANT NUMBER

How many participants do you plan to recruit?

Please briefly explain why the number is appropriate to answer the study's research question(s).

Needed 20 Participants

3.2 PARTICIPANT CHARACTERISATION

What age-range of participants will you recruit?

18 years old or older

Please list the principal inclusion and exclusion criteria.

- Have normal or corrected to normal vision
- Do not have any motor or communication impairing disabilities and,
- Are not taking any medications affecting brain chemistry.

Click here to enter text.

3.3 RECRUITMENT

Please describe the recruitment process and append any advertising if used.

3.4 NHS AND SOCIAL SERVICES INVOLVEMENT

Will participants be recruited because of their status as NHS patients or Social Services clients, or identified through those services' records?

☐ Yes
☒ No

If "yes", please give details of current status of the HRA REC review.

Click here to enter text.

Will the study involve adult participants unable to consent for themselves as defined by the Mental Capacity Act 2005 or other vulnerable adults?

☐ Yes
☒ No

If "yes", please detail the associated procedures as set out in the HRA REC application.

Click here to enter text.

CHECKLIST

1. The Application form has the appropriate signatories	Yes	
2.The Participant Information Sheet includes a statement to the effect that the project has been reviewed by the appropriate Research Ethics Committee and has been given a favourable ethical opinion for conduct.	Yes	
3. The Participant Information Sheet contains the relevant Data Protection information.	Yes	
4. EITHER	a) The proposed research will not generate any information about the health of participants;	☒
OR	b) If the research could reveal adverse information regarding the health of participants, their consent to pass information on to their GP will be included in the consent form and in this circumstance I will inform the participant and their GP, providing a copy of the relevant details to each and identifying by date of birth.	☐
OR	c) I have explained within the application why (b) above is not appropriate.	☐
5. EITHER	a) The proposed research does not involve children under the age of 5;	☒
OR	b) My Head of School (or authorised responsible person) has given details of the proposed research to the University's insurance officer.	☐
6. EITHER	a) The proposed research does not involve the taking of blood samples:	☒
OR	b) For anyone whose proximity to the blood samples brings a risk of Hepatitis B, documentary evidence of immunity prior to the risk of exposure will be retained by the Head of School or authorised responsible person.	☐
7. EITHER	a) The proposed research does not involve the storage of human tissue, as defined by the Human Tissue Act 2004;	☒
OR	b) I have explained within the application how the requirements of the Human Tissue Act 2004 will be met.	☐
8. EITHER	a) The proposed research does not involve the use of ionising radiation;	☒
OR	b) I am aware the proposed research will require HRA REC review.	☐

VERSION CONTROL

VERSION	KEEPER	REVIEWED	APPROVED BY	APPROVAL DATE
1.0	UREC	Annually	UREC	Sept 18

Researcher (principal): Dr Yoshikatsu Hayashi
Email: y.hayashi@reading.ac.uk
Phone: +44 (0) 118 378 6701

Researcher (role): Ozge Saracbasi (PhD Candidate)
Email: o.o.saracbasi@pgr.reading.ac.uk

School of Biological Sciences
Biomedical Engineering Section
University of Reading
Reading RG6 6DH

INFORMATION SHEET

Project Title: Neural Correlates of Haptic Interaction in a Cooperative Task

Why are we doing this study?

Previous research (Avila Mireles et al., 2017, 'Skill learning and skill transfer mediated by cooperative haptic interaction') has shown that when two people cooperate with each other to achieve a joint task (a task requiring coordination and cooperation between the partners, such as dancing tango), they faced dual instabilities arising from the environment (i.e. unknown environment with external nonlinear forces) and interaction with a partner (i.e. the person performing the task together).

In previous studies, we identified the behavioural correlates of haptic interaction between paired participants to explain the dual instability problem. In light of the previous studies in this study we aim to identify the neural correlates of coordinated motion between paired participants to investigate the dual instability problem.

What is the purpose of the study?

We will investigate how the functional brain network is affected from interaction with a partner through haptic interaction in the presence of an unknown external force field.

Who is eligible to participate in the study?

We are looking for healthy volunteers who

- Are 18 years old or older
- Have normal or corrected to normal vision
- Do not have any motor or communication impairing disabilities and,
- Are not taking any medications affecting brain chemistry.

How can you get involved?

If you would like to participate, please email Ozge Saracbasi at o.o.saracbasi@pgr.reading.ac.uk.

Do I have to take part?

Participation is entirely voluntary, and you can withdraw at any time without giving a reason, and this will be without detriment.

What will be involved if you take part?

In the experiment you will be asked to perform a task with a partner who will be randomly chosen and assigned to work with you. You will be asked to perform the task while wearing an EEG cap with 32 gel-based electrodes to record your brain waves during the experiment. EEG is non-invasive and safe.

We use an abrasive electrolyte gel (similar in action to a cosmetic exfoliating scrub) and 70% isopropyl alcohol in order to clean the surface of the scalp at points of contact with the electrodes to improve the electrical contact with the skin. The gel is hypoallergenic and hence is suitable for subjects with sensitive skin. On rare occasions isopropyl alcohol may case mild allergic reactions in people with previous skin conditions such as eczema or skin ulcers. If you have such conditions or have a history of strong allergic reactions, you should not participate in this experiment.

The experiment lasts about 2 hours including setting up EEG equipment. The experiment involves four phases, with a break in the middle. Each phase will consist of multiple repetitions of the same task. The task involves participants holding the tip of a robotic device created in our lab and, together with their partner, moving a cursor to a randomly placed target on the computer screen. Their partner will be sitting in a separate room interacting with a similar robotic device. The robotic device can be thought of as a way to share people's intentions with each other. The robotic devices used by two participants will be connected with virtual springs. That is to say, the participants' movements will affect and be affected by their partner's movements through this robotic device and virtual spring.

Apart from your EEG data, we will also be recording the forces exerted by participants on the robotic device, along with the acceleration, position and velocity of the robotic devices during the experiment. We will also request that you fill in a brief questionnaire after you have completed the trials. You might want to wash your hair after the experiment to remove the gel from your hair. We have a hair washing sink with handheld shower and hot water in the lab. We also provide a towel, shampoo and hair dryer. Prior to starting the experiment, you will be asked to provide written informed consent and to complete a questionnaire about your gender, date of birth and handedness.

Confidentiality, storage and disposal of information

You will be asked to provide your name and to sign a consent form so that we can keep a record of your participation in the study, however, this information will be kept confidential and will not be disclosed publicly. The consent form will be stored in a locked filing cabinet in our lab, and destroyed securely 5 years after completion of the project.

All data from the study will be stored, processed, and reported using a pseudonymous user ID. It will be reported only as a part of an aggregate dataset collected from multiple participants. Hardcopies of the questionnaire will be transcribed into electronic form, and the hardcopies stored in a locked filing cabinet in our lab, separate from the consent forms, and destroyed 5 years after completion of the project. The questionnaire data will be used to understand the relationships that emerge between you and your study partner and will not be used to identify you in any way.

Pseudonymised haptic data and pseudonymised EEG data will be stored securely and password protected on the internal Brain Embodiment Lab server provided by the university, accessible to members of the research team now and in the future.

Are there any benefits/risks to taking part [e.g. health]?

There are no benefits or health risks to taking part in this experiment. EEG is a completely non-invasive and safe procedure. EEG sensors on the scalp might cause slight discomfort at the end of the experiment. As discussed above, there is a possibility of skin irritation and/or allergic reaction arising from application of the EEG sensors. Also, you might feel fatigue because of the movement repetition involved in reaching a target.

What will the results of the study be used for?

The results of this study will contribute towards PhD research and scientific publications. If you would like to learn the results at the end of the study, please contact the researchers.

What payment will be made for participation in the study?

You will be remunerated for your time and participation with £10 per each hour (£20 in total).

Where will the studies take place?

The study will take place in the Brain Embodiment Lab, Biomedical Engineering, located in the Polly Vacher building on the University of Reading's Whiteknights campus. A researcher will contact you to provide further directions, and to arrange a time slot for you.

Who has reviewed the study?

This project has been subject to ethical review, according to the procedures specified by the University Research Ethics Committee and has been given a favourable ethical opinion for conduct.

Contact details for further questions:

Experiments and the research will be conducted by Ozge Saracbasi (o.o.saracbasi@pgr.reading.ac.uk) who is currently a 3rd year PhD researcher in Biomedical Engineering.

Ozge is supervised by Dr Yoshikatsu Hayashi and Prof William Harwin.
Contact details: PI Name: Yoshikatsu Hayashi
Email: y.hayashi@reading.ac.uk Phone: +44 (0) 118 378 5024

In the event of a complaint

If you have any comments or if you have a complaint, you can contact the Chair of the Ethics Committee of the School of Biological Sciences, Dr M. Alejandra Perotti Email: m.a.perotti@reading.ac.uk

Thank you for your help.

Investigator Contact Details:

Dr. Yoshikatsu Hayashi	Ozge Saracbasi
e: y.hayashi@reading.ac.uk	e: o.o.saracbasi@pgr.reading.ac.uk

Appendix C: data protection for information sheets

The organisation responsible for protection of your personal information is the University of Reading (the Data Controller). Queries regarding data protection and your rights should be directed to the University Data Protection Officer at imps@reading.ac.uk, or in writing to: University of Reading, Information Management & Policy Services, Whiteknights House, Pepper Lane, Whiteknights, Reading , RG6 6UR, UK.

The University of Reading collects, analyses, uses, shares and retains personal data for the purposes of research in the public interest. Under data protection law we are required to inform you that this use of the personal data we may hold about you is on the lawful basis of being a public task in the public interest and where it is necessary for scientific or historical research purposes. If you withdraw from a research study, which processes your personal data, dependant on the stage of withdrawal, we may still rely on this lawful basis to continue using your data if your withdrawal would be of significant detriment to the research study aims. We will always have in place appropriate safeguards to protect your personal data.

If we have included any additional requests for use of your data, for example adding you to a registration list for the purposes of inviting you to take part in future studies, this will be done only with your consent where you have provided it to us and should you wish to be removed from the register at a later date, you should contact…… **Ozge Saracbasi** ………..

You have certain rights under data protection law which are:

- Withdraw your consent, for example if you opted in to be added to a participant register
- Access your personal data or ask for a copy
- Rectify inaccuracies in personal data that we hold about you
- Be forgotten, that is your details to be removed from systems that we use to process your personal data
- Restrict uses of your data
- Object to uses of your data, for example retention after you have withdrawn from a study

Some restrictions apply to the above rights where data is collected and used for research purposes. You can find out more about your rights on the website of the Information Commissioners Office (ICO) at https://ico.org.uk

You also have a right to complain the ICO if you are unhappy with how your data has been handled. Please contact the University Data Protection Officer in the first instance.

The details of the existence of automated decision-making, including profiling (if applicable – more information on whether this would apply to your study can be found here: https://ico.org.uk/for-organisations/guide-to-the-general-data-protection-regulation-gdpr/individual-rights/rights-related-to-automated-decision-making-including-profiling/

APPENDIX B: SAMPLE CONSENT FORM

Consent Form

Please mark your initials in the box after each statement to confirm it has been read and agreed to.

1. I have read and had explained to me by …**Ozge Saracbasi**.… the accompanying Information Sheet relating to the project on: …**" Neural Correlates of Haptic Interaction in a Cooperative task"**…

2. I have had explained to me the purposes of the project and what will be required of me, and any questions I have had have been answered to my satisfaction. I agree to the arrangements described in the Information Sheet in so far as they relate to my participation. ☐

3. I have had explained to me what information will be collected about me, what it will be used for, who it may be shared with, how it will be kept safe, and my rights in relation to my data. ☐

4. I understand that participation is entirely voluntary and that I have the right to withdraw from the project any time, and that this will be without detriment. ☐

5. I understand that the data collected from me in this study will be preserved, and subject to safeguards will be made available to other authenticated researchers. ☐ *****

(*Guidance note only safeguards will include pseudonymisation, data minimisation, secure transfers, and any necessary data sharing and confidentiality agreements between parties)

6. This project has been reviewed by the University Research Ethics Committee and National Research Ethics committee where relevant and has been given a favourable ethical opinion for conduct.

7. I have received a copy of this Consent Form and of the accompanying Information Sheet. ☐

Name: ………………………………………………………………………………

Signed: …………………………………………...………………………………

Date: ……………………………………………………...………………………

I am happy to be included on a register of research participants for the purposes of being contacted about further studies by…… **Ozge Saracbasi** …….. Please mark with your initials ☐ (optional)

Subject Information

Participant ID:

Age:

Gender: male / female / other / prefer not to say

Handedness: right handed / left handed

Post Experiment Questionnaire

Participant ID:

Please answer the following questions using a scale from 0 to 5 with 0 = strongly disagree and 5 = strongly agree.

1) I felt the task was difficult to complete.

0	1	2	3	4	5

2) I felt the task was performed cooperatively.

0	1	2	3	4	5

3) I felt that the task became easier with successive trials.

0	1	2	3	4	5

4) I felt that my partner and I performed well during the task.

0	1	2	3	4	5

5) I was able to feel haptic guidance.

0	1	2	3	4	5