Modeling and Analysis of Multimodal Collaborative Virtual Interaction for Autism Spectrum Disorder Intervention

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CHAPTER 1

INTRODUCTION

1.1 Research Goals

Autism spectrum disorder (ASD), characterized by deficits in communication and social interaction together with restricted, repetitive and stereotyped patterns of behavior, represents a range of neurodevelopmental disabilities [1-3]. One in 59 children are diagnosed with ASD in the US [4] [5], with prevalence rates amongst school-aged children (6-17 years) increasing from 1.16% to 2.00% between 2007 and 2012 [6]. Although ASD is a life-long disorder with no known cure, the literature has shown that intensive educational practices and behavioral interventions make positive impact on the lives of children with ASD [7, 8]. However, conventional ASD interventions for ASD are costly, inaccessible and inefficient due to limited resources and weak motivations [9-12]. It is estimated that the average lifetime cost for ASD care is up to $3.2 million on average for individuals with ASD and their families [13]. Therefore, the development of a novel ASD intervention paradigm which can provide low-cost and efficacious treatment options for a broader ASD population is important and needed.

Recently, computer-assisted ASD interventions have shown potential for addressing the limitations of the conventional ASD interventions, due to their low-cost, their appeal to children with ASD, and their relatively broader access. Many children with ASD exhibit a natural affinity for computer technologies that leads to a higher level of engagement and fewer disruptive behaviors in computer-based interactions [12, 14]. In particular, virtual reality (VR) technologies that allow users to actively participate in the interactive and immersive simulated situations have been used to provide an attractive, replicable, quantitatively measurable, and controlled intervention environment with real-time feedback [15, 16]. A few VR-based systems have been developed to investigate and teach important living skills, such as driving skills [17], and social skills [18], to children with ASD, and results suggest that children were able to appropriately understand, use and react to virtual environments with the possibility of transferring theses skills to real life. Communication and social interaction deficits are the most striking features of ASD. Many children with ASD have difficulty developing the social competence required for appropriately interacting with peers, which may lead to poor social-emotional reciprocity, misuse of verbal or non-verbal behaviors, and inappropriate relationships [19, 20]. Research has shown that compared to their typically developing (TD) peers, children with ASD may experience greater loneliness and difficulties in developing satisfying friendships and social networks, even though they themselves expect social involvement [21, 22].

Cascading effects of these social challenges could also prevent children with ASD from living independently, limiting their opportunities and straining resources across systems of care. However, most existing VR-based intervention systems are designed for a single user, and can only provide restricted communications and interactions with the virtual environment or the programmed virtual avatar. In such systems, it is difficult to implement complex and spontaneous interaction similar to peer-based interaction within VR environment. Recent evidence suggests that children show improvements in learning, communication and sociability when working or playing collaboratively with others [23]. Collaborative virtual environments (CVE), as compared to single user VR environments, address the shortcoming of the VR environments and enable multiple users in distributed locations to communicate and interact freely with one another within a shared virtual setting using a computer network. Children with ASD can navigate the shared virtual world as well as communicate (verbally or non-verbally) to share information [24] and thus can benefit from peer-based interaction. However, the majority of existing CVE systems for ASD intervention only consider the sequential interaction where users take turns to interact with the VE to implement different sub-tasks in order to achieve a common goal. Another important interaction mode, simultaneous interaction that requires the users to interact with the VE at the same time, are underexplored. Therefore, one goal of this research is to design CVE systems that are able to provide realistic and flexible social communication and interaction training environments that can support both sequential and simultaneous interactions between users.

Skill practice is critical to apply learned social skills beyond the training setting. For children with ASD, social activities involve a lot of play and sport activities that require proficient motor skills to participate with success [25]. However, motor skill deficits are present and persist among children with ASD, and are estimated to occur in 90% of the ASD population [26-30]. Compared to extensive ASD research focusing on the social deficits of ASD, motor deficits of children with ASD and the influence of motor skills on social skills of children with ASD are still underexplored. In particular, there is evidence that children with ASD show motor coordination deficits and delays in fine motor skills compared to their typically developing (TD) peers [31-33]. Fine motor skills that coordinate the use of the fingers and hand with visual perception are commonly used in activities of daily life that require precision and steadiness, such as handwriting and tool manipulation [34]. Atypical fine motor control has been found among children with ASD, such as abnormalities in grasping and reaching [33], eye-hand coordination [35], and handwriting skills [36]. These children might have poor motor planning and control, take a longer time to respond to valid cues or initialize a movement, exhibit increased movement duration and excessive associated movements, and find it difficult to negotiate complex movement [29, 32, 37, 38]. Studies have shown that children's fine motor skills may be an indicator of later achievements [39, 40], and fine motor deficits might negatively affect children with ASD in physical, scholastic and social activities [41-43]. However, relatively less research has attempted to address these motor deficits, especially by taking advantage of advanced technology. Fine motor tasks require a longer duration of attention and physical effort. Fine motor tasks in the form of computer games can deliver consistent and real-time rewards or consequences for responses, which can encourage engagement and retain children's attention [44]. Especially with the haptic devices, children are able to "feel" the effect of their manipulations and interactions with the virtual environment in the form of force feedback. Several studies have reported that haptic devices are beneficial in increasing immersion and quality of task performance and thus enhancing training achievements [45-50]. Though a few studies have realized the importance to investigate the fine motor deficits of children with ASD, most of them focused on atypical hand movement manipulation and ignored the importance of grip control [33, 51-54]. Considering the importance of grip control in fine motor manipulation [33, 51-54], one of my research interests is to design haptic VR-based systems for children with ASD that can provide opportunities for assessing and practicing fine motor skills using systematically designed tasks that require both hand motion and grip control. In addition, considering that motor skill deficits might hinder the social interaction of children with ASD, one of my research interests is to investigate how the fine motor skill affects the social skill of children with ASD.

Though VR-based training systems have shown promise for expanding the accessibility of a wide range of ASD intervention and resources, these systems are not always efficacious due to the limitations in flexibility and interactivity [55, 56]. Some of such systems provides little flexibility to adapt the training contents and process to meet the user's needs and ability. Some could not provide instant feedback and guidance to support the interactive training. Even though the CVE-based training system can support flexible communication and interaction of multiple users, it is not easy to find time- and ability-matched partners for children with ASD. Inappropriate partners might reduce engagement as well as training achievement. Thus, it is necessary to develop adaptive training systems that can recognize the user's performance and allow the user to proceed with the intervention at their own pace. The intelligent agent technology is one solution to support the adaptive interaction between the user and the system, and has been increasingly used in the fields of education and therapy. An intelligent agent has the capability of automatically perceiving the user's behaviors and appropriately responding to the user with the human-style intelligence [57]. A few studies have attempted to design intelligent tutors to help children with ASD practice communication skill and language skill [56, 58]. However, most existing intelligent agent systems have limited autonomy. Such agents are either pre-programmed with limited responses or controlled by a professional trainer. In addition, few agents are able to interact with the user haptically in addition to converse with the user. Therefore, one of the goals of this research is to design and develop an autonomous intelligent agent that can be a virtual partner with the haptic interaction capability within the VR environment to assist the collaborative training of children with ASD in order to ease the demand for such training from peers, parents or professional trainers.

The research presented here focuses on the design, development and application of CVE systems and intelligent VR-based systems for ASD intervention. This research aims to: (1) develop CVE systems that can support realistic interactions and flexible conversations between children with ASD and their peers, (2) develop haptic VR-based systems that can analyze and improve fine motor skills of children with ASD as well as investigate the impact of fine motor skill on the social skill of children with ASD, and (3) develop an intelligent agent with the haptic interaction capability that can support human-to-agent communication and interaction within the VR fine motor training system, in order to facilitate adaptive training and autonomous conversation pattern analysis. This research provides a novel ASD intervention paradigm that can assist conventional ASD interventions, reduces the burden on ASD intervention resources and expand accessibility to effective ASD interventions.

The rest of this chapter is organized as follows. Section 1.2 discusses the related work on computer-assisted systems for ASD intervention. Section 1.3 summarizes my completed research work.

1.2 Computer-Assisted Systems for ASD Intervention

Given the limited ASD intervention resources in the healthcare system [59] and with the documented affinity of many children with ASD for technology [9], a number of computer-assisted systems have been developed for ASD intervention in recent years with several benefits [60]. First, these systems create a controllable intervention environment with minimal distractions. Children with ASD often have difficulty filtering primary information from complex and fast-changing scenarios. Computer-assisted systems can control and simplify the input stimuli, divide the complex process into small processes and allow repeated practice, and thus provide a safe, predictable and consistent intervention environment. Second, computer-assisted systems can deliver engaging elements in the forms of visual, auditory or haptic feedback and provide real-time responses to the user's actions, which can enhance the user's engagement. In addition, individualized intervention environment can be provided to fit the user's deficits and ability, and objective assessment can be achieved based on the performance data recorded in real time. With these benefits, computer-assisted systems are promising as a novel ASD intervention tool to assist the assessment and training of impaired skills in children with ASD.

Since this work aims to design computer-assisted systems for assessing and training social skill and fine motor skill of children with ASD, the literature reviews in the following subsections focus on the technologies related to these two topics. First, we begin with the early computer-assisted systems that are developed as substitution for therapist-based intervention to elicit better intervention results. These systems generally use traditional interactive tools, such as mouse, keyboard and monitor, and provide/collect interaction information in the form of text, image, audio or videos. Most of these systems are designed for individuals with ASD to learn and practice specific behavioral skills. Next, the intervention systems using virtual reality (VR) technologies are introduced. These systems usually employ novel interactive tools, such as joystick and eye tracker, to support interactions between the user and the virtual environments or avatars. Virtual intervention environments can mimic real-life scenarios, and allow the user to interact/communicate with the virtual elements and obtain real-time feedback on his/her actions, which may make generalization of skills learned from the virtual environments. Finally, the studies using intelligent systems for ASD intervention are presented. These systems usually use advanced technologies, such as artificial intelligence (AI) and human-computer interaction (HCI) methodologies, to implement an autonomous detection and response system that can support human-like interaction between the user and the system.

1.2.1 Conventional Computer-Assisted Systems

The earliest and broadest use of computer technologies in ASD intervention is the Multimedia-based intervention system, which can provide attractive intervention contents and feedback to motivate children with ASD in the intervention. Heimann et al. [61] used an interactive multimedia computer program, Alpha, as a supplementary instruction tool for teaching the reading and communication skills in children with ASD. The Alpha program provided multichannel feedback (e.g., audio, video and sign language) to foster language learning. The study with 11 children with ASD indicated improved word reading and phonological awareness as well as increased enjoyment by using the Alpha program. They concluded that using motivating multimedia programs could stimulate reading and communication during the intervention. Hetzroni et al. [62] explored the effectiveness of a computer intervention program for teaching specific communication functions to children with ASD. The computer software simulated three daily activities including play, food, and hygiene as the training settings. They conducted a study with five children with ASD and found the communication measures related to echolalia, relevant and irrelevant speech and communicative initiations showed improvement after using the computer program. They also claimed that the computer program could enhance use of appropriated functional communication in natural settings. These works with other pioneering works that used these simple multimedia software to improve vocabulary acquisition [63], improve emotion understanding [60], social communication skills [64] of children with ASD have demonstrated the potential for success of computer-assisted intervention for remediating communication and social interaction difficulties of children with ASD. However, these systems are always limited by their ability to provide only simple, less flexible one-way interaction between the user with the computer that may not scale up to generalize to real-world activities.

1.2.2 Computer-Assisted Systems using Virtual Reality Technologies

In the 1990s, the development of virtual reality (VR) technologies and interactive technologies provide an opportunity for individuals with ASD to actively participate in the intervention process instead of being passive recipients. Virtual reality (VR) technologies refer to using computer graphics to simulate a real or imaginary environments (VE) and avatars [15]. Novel interactive tools like joystick and special digital displays like head-mounted display (HMD) are often used with VR to improve the interactive experience. A number of early VR applications for ASD intervention have suggested that children with ASD are able to focus on and interact appropriately with VEs, and finally use the learnt social skills from the VR intervention systems in the natural environments [65-68]. Parsons et al. [69] designed a virtual café with a series of tasks for social skills training. The user could navigate around virtual environments with a joystick and interact with virtual objects using a mouse. The areas of interaction could provide textual prompts for the user to respond. Their study with 12 children with ASD and 12 paired typically developing (TD) children found that children with ASD learned to use the system quickly and showed significant improvements. Specially, avatars have been used in several studies as the interaction medium [58, 70, 71]. Hopkins et al. [71] used a computer-based training program with animated avatars to teach children with ASD specific social skills, such as responding to joint attention, recognizing facial expressions and faces. The avatars could interact with the children based on a pre-programmed knowledge base. They conducted a study with 49 children with ASD and found practicing in the interactive system with avatars could help improve children's social skills in a natural environment.

Motor impairments, until recently, have rarely been investigated especially compared to the social impairments in autism research. However, recent studies have suggested the high prevalence of motor impairments and delays among ASD population [27]. Motor impairments among the ASD population has begun to gain more research interest in recent years. Instead of using paper assessment materials conducted by specialists or taking training under the supervision of professional motor skill trainers in the real world, motor skill assessment and training in the form of computer tasks/games are more likely to be accepted among children with ASD, and are able to provide computational measures and precise quantification of the motor signature throughout the intervention process. VR technologies combined with advanced sensors and devices (e.g., haptic device and touch screen) can provide augmented performance feedback, such as incorporating the sense of the touch, and may facilitate more realistic interactions between the user and the VR environments, which possibly encourage engagement and enhance training achievements. A few studies have explored children's fine motor skills through handwriting analysis. For example, Rosenblum et al. [72] indicated the unique handwriting characteristics of children with high-functioning autism spectrum disorder (HFASD) (age: 9-12) by using a computerized instrumentation consisting of a tablet, where the user performed writing tasks. They suggested that identifying ASD-specific handwriting features could provide a more comprehensive picture of individual deficits, and may contribute to more focused and adaptive intervention. Kim et al. [73] developed a haptic assisted training (HAT) system for transferring and improving handwriting skill. The HAT system guided the user's hand along a sequence of strokes and provided the training tasks in the form of 3D games. They implemented the systems with two different haptic devices, Phantom Omni and Novint Falcon, and tested the systems with children (age: 6-11) grouped by typical and special need. The system was found to be well received by the children, who showed improvements in tracing alphabets.

Though VR-based intervention systems have advantages in providing safe, controllable and replicable assessment and training environments, most existing VR-based intervention systems are designed for a single user and can only provide restricted communications and interactions with the virtual environment or the programmed virtual avatar. Such systems are difficult to implement complex and spontaneous interaction similar to peer-based interaction within VR systems.

1.2.3 Computer-Assisted Systems using Collaborative Virtual Environments (CVEs)

Evidence suggests that children show improvements in learning, communication and sociability when working or playing collaboratively with others [23]. Especially, age-matched typical peers are thought to be the effective role models for children with ASD to reinforce social functioning [74]. In order to introduce technology that can foster such collaborative learning, a collaborative virtual environment (CVE) that supports communication and interaction among multiple users within a shared VE has been proposed. CVEs provide opportunities for children with ASD to practice social skills with real people in more natural and flexible interactive environments. One thread of CVE applications is to facilitate face-to-face interaction in a co-located interaction system [75-77]. These applications always employ the touchscreen devices, such as tablets and large displays, to support multiple inputs. For instance, Battocchi et al. [77] designed a collaborative puzzle game featured with enforced collaboration on the tabletop to facilitate cooperative behaviors in children with ASD. To move a digital puzzle piece, two players needed to touch and drag it simultaneously. In two studies including 70 TD children and 16 children with ASD, they found that enforced collaboration was related to the increase of negotiation moves and coordination of the shared activity. Another emerging CVE application is for tele-rehabilitation that allows remote interaction by minimizing the barriers of distance, time and cost [78]. The distributed CVE systems could reduce the complexity of social rules in real-world situations as well as the pressure emerging from face-to-face communication for some children with ASD. Stichter et al. [79] designed a distributed 3D CVE, *iSocial*, for children with ASD to complete collaborative tasks (e.g., to design and build a restaurant) in the shared virtual environment. Their study with 11 children with ASD indicated that social competence curriculum could be delivered with fidelity in CVE and their approach brought social competence benefits for children with ASD.

Though a few of research works have noticed the promise of the distributed CVE systems for investigating the social deficits of children with ASD [80, 81], the utility of the distributed CVEs in ASD interventions remains in its infancy, and most of these systems only investigate the sequential interaction (i.e., users take actions by turns) and ignore the simultaneous interaction. In addition, most distributed CVEs in ASD interventions are only designed to provide audio-visual interfaces and ignore the importance of haptic communication in social interaction. However, a few studies have suggested that social touch can profoundly influence social communication and interaction [82]. Simulating the sense of touch and contact in CVEs could enhance feelings of social presence and task performance [83, 84]. Tactile or kinesthetic interfaces have been used to enable haptic interaction between people who are physically apart. For example, Hossain et al. [85] integrated haptic interactions with the multiuser game, Second Life, through a haptic-jacket system, facilitates the exchange of touch cues resembling encouraging pats and comforting hugs between users and their respective avatars. They claimed that emotional feedback that is fundamental to physical and emotional development in turn could enhance the users' interactive and immersive experiences.

1.2.4 Computer-Assisted Systems with Intelligent Agent

By using the technologies of artificial intelligence (AI) and human-computer interaction (HCI), an intelligent agent system has the capability of automatically perceiving the user's behaviors and appropriately responding to the user with the human-style intelligence [57]. Intelligent agent systems have several advantages for ASD intervention. First, intelligent agent systems can provide intensive one-to-one intervention and thus ease the demand for such intervention from professional trainers, peer partners and parents. Second, individual with ASD from different backgrounds differ in terms of motivation, learning styles and learning skills. A one size-fits-all method would result in ineffective intervention. Intelligent agent systems with performance criteria can potentially monitor the user's learning process and provide meaningful feedback and guidance, and thus support adaptive intervention to match the user's needs and pace. Third, some children with ASD have difficulties of accurately expressing their own emotions [86]. Intelligent agent systems with special sensory input device, such as an electroencephalogram (EEG), can potentially assess the cognitive state of the user according to the detected physiological signals and thus can arrange appropriate tasks to reduce discomfort and increase engagement.

A few studies have used intelligent agent systems to address the language skill [58], and social skill [56, 87, 88] of children with ASD. However, most intelligent agents are designed with no or little autonomy, which still lead to great resource demand. For example, Mower et al. [89] utilized a virtual conversational agent, Rachel, as an emotional coach to interact with children with ASD in a set of emotion problem-solving tasks. Rachel was designed using the Wizard of Oz (WoZ) paradigm, and was remotely controlled by a wizard using a control panel to select an action from a limited set of pre-defined available actions. Their pilot study with two children with ASD suggested that Rachel was effective to elicit social conversational behaviors of children with ASD. Only a few studies have been contributed to develop the fully autonomous agents. For example, Milne et al. [87] developed a virtual social tutor, Thinking Head, for teaching social skills (facial recognition and social situational understanding) to children with ASD with the ability to realistically portray facial expressions. Thinking Head could generate appropriate speech and facial expressions according to the user's inputs (e.g., clicking choice buttons and typing texts) on the interface. Their experiments with 14 children with ASD demonstrated significant overall performance improvements of participants in the post-test and positive feedback of the system used for social skill education from participants and their caregivers. However, users were not allowed to engage in a spoken conversation with the Thinking Head, which put limits on the generalizability of learnt skills in actual social interactions. Bernardini et al. [56] developed an intelligent game, ECHOES, for fostering social communication in children with ASD. The system includes a virtual agent, who can interact with the user verbally using simple language (e.g., "My turn!" and "Good job!") and/or non-verbally through gaze and gestures (e.g., pointing at an object) and act autonomously. Their experimental results from 29 children with ASD indicated encouraging tendencies of the use of agent for a number of children with ASD, though no significant transfer of social communication skill were found across all children with ASD.

Though fully autonomous agent systems have recently attracted more attention in the field of ASD research, most autonomous agents focus on teaching children with ASD specific skills (e.g., teaching the appropriate responses to a predefined set of social situations) rather than on providing spontaneous social interaction experiences. In addition, to our knowledge, no intelligent agent system exists allowing children with ASD to interact with the agent haptically in addition to converse with the agent. Agents with haptic feedback have been explored in the research fields of emotion expression recognition [90], skill training and coaching [91] and social interaction [92]. For example, Huisman et al. [92] developed an embodied conversational agent that could touch the user's forearm. The user, wearing a vibrotactile display, could view his/her forearm through a tablet running an AR application. When the agent's hand visually touches the user's arm, vibrotactile feedback is generated in the same location, simulating a touch by the agent. However, most existing research focuses on social affective communication through haptic feedback that is not purely task oriented. Haptic agents that can perform joint actions with the user have recently gained much attention in the research field of physical human-robot interaction (pHRI). Such agents could interact with humans in different modalities, such as verbally through speech and also non-verbally through gestures and the sense of touch [93]. Several haptic agents have been developed as assistive devices for industry [94] and for physical rehabilitation [95-97]. For example, Yokoyama et al. [98] developed a humanoid robot HRP-2P that can implement cooperative works with a human. The robot can carry an object cooperatively with a human by biped locomotion according to the voice commands by the human. A cooperative control is applied to the arms of the robot while it carries the object, and the walking direction of the robot is controlled by the interactive force and torque through the force/torque sensor on the wrists. However, most existing haptic agents could only accept commands from the humans or only perform independent tasks where few interactions exist between the agents and the humans. A very limited number of research works have contributed to implement interaction beyond simple and passive cooperation, by introducing role switching and continuously adapting interaction [99-101].

1.3 Scope and Summary of the Dissertation Research Work

This dissertation research focuses on the design, development and application of VR-assisted systems for the intervention of two ASD impairments: (1) communication and social interaction skill, and (2) fine motor skill, in order to assess, analyze and improve these skills in a more efficient and accessible way. Six studies have been completed to achieve the research goal. Each study is briefly introduced in the sub-sections, while the details are discussed in Chapter 2 to Chapter 7.

The first study aimed to investigate and promote the communication and social interaction skills of children with ASD. In order to provide flexible intervention environments, a CVE-based interaction system was developed that can support multi-user interactions from remote locations. In addition, a gesture-based interactive tool, Leap Motion [102], was used instead of the keyboard and mouse, in these systems to provide a more immersive and naturalistic interaction environment. The study results indicated the positive impact of such CVE systems on communication and interaction skills on both children with and without ASD.

The results of the first study indicated that participants showed varying abilities in controlling the virtual objects through gestures, which could affect their social interaction with partners. Thus, the second and the third study focused on the fine motor skill training of children with ASD separately with a tablet game system and a Haptic-Gripper VR system. The tablet game system was developed to assess the hand preference and hand movement skill of the children with ASD, and the study results found different hand usage patterns among children with ASD and their TD peers. The Haptic-Gripper VR system could provide analysis and practice opportunities of grip control skill and hand movement skill of children with ASD in an adaptive virtual environment with real-time auditory, visual and haptic feedback. The results indicated the improvements of participants in accuracy and steadiness of movement and force control, as well as the differences of fine motor patterns between children with ASD and their typically developing (TD) peers.

Given that motor skill might affect the social skill practice of children with ASD, and children require the coordination of many different skills in daily life [103-105], we planned to investigate the impact of the fine motor skill on the social skill of children with ASD during performing the collaborative fine motor tasks after the third study. To achieve that goal, a CVE environment allowing users to perform collaborative fine motor tasks using haptic devices was needed. Therefore, we first tested and compared the performance of three control architectures for implementing the Collaborative Haptic Virtual Environment (CHVE) in the fourth study. Then we improved the Haptic-Gripper system (Hg) to a Collaborative Haptic-Gripper system (C-Hg) by using a centralized control architecture. This system allows users to perform individual fine motor tasks as well as collaborative fine motor tasks with remote partners. The study results presented significant performance improvements of participants in both individual and collaborative fine motor skill training tasks, suggesting the potential of the C-Hg system for simultaneously improving fine motor and social skills, with implications for impacts of improved fine motor skills on social outcomes.

Though children with ASD can benefit from performing training tasks with real partners under the flexible interaction environment, it is difficult to find time-matched or ability-matched partners. Inappropriate partners might reduce engagement as well as training achievement. In addition, the unrestricted conversations occurred during the peer-based interactions make it resource-intensive to manually analyze the communication patterns of the users. Therefore, an Intelligent Collaborative Haptic-Gripper system (INC-Hg) was developed which can provide an agent who can understand, communicate and haptically interact with the user. The results indicated that the system could classify the participant's utterances into five classes with the accuracy of 70.34%, which suggested the potential of INC-Hg to automatically recognize and analyze conversational content. The results also indicated high accuracies of the agent to initiate a conversation (97.56%) and respond to the participants (86.52%), suggesting the capability of the agent to conduct proper conversations with the participants.

1.3.1 Hand-In-Hand: Collaborative Virtual Reality Systems for Social Interaction

As CVE can support multi-user interaction from remote locations and provide an interaction platform for human-to-human communication and cooperation, we developed two types of CVE systems for investigating and promoting social communication and interaction skills of children with ASD. Chapter 2 presents the development and application of these CVE systems.

(1) A Collaborative Virtual Reality System

The collaborative virtual reality system, named Hand-in-Hand, provided a series of collaborative games that could foster interactive behaviors between the players. These games integrated with the Leap Motion based gesture recognition capabilities offered a chance for players to control the virtual game elements in the CVE with their hands. Two virtual collaborative tools using Leap Motion technology that required two different cooperative modes (one with the common goal, and one with the individual goal) were developed. The Hand-in-Hand system also provided objective and quantitative performance metrics for a better understanding of the players' communication and interaction skills.

We conducted a usability study to evaluate the Hand-in-Hand system with six children with ASD and six TD children. All participants were paired based on age and gender and divided into 6 ASD/TD pairs. Each pair of participants stayed in separate rooms to complete three sessions (pre-test, training session, and post-test) of collaborative games. The pre- and post-tests were used to compare the performance change of participants regarding their communication and interaction skills.

Participants showed improvements in cooperation considering the increased completed pieces and cooperative ratio, and the reduced play time. As for the verbal-communication, participants with ASD spoke more words in the end.

(2) A Communication-Enhancement Collaborative Virtual Reality System

In order to foster information sharing and communication, a communication-enhancement mode was integrated in the Hand-in-Hand CVE system that provided gaze- and voice-based communication within the game play. The new mode slowed down the pace of the game and created more opportunities for users to pay attention to their partners and communicate with each other.

By following the same experimental procedure as that in the previous CVE study, six ASD/TD pairs of participants participated in the usability study for the communication-enhancement CVE system. The study results indicated that participants cooperated progressively better and communicated more frequently in these games. In addition, participants using this system achieved greater improvement, compared to those using the CVE system without the newly integrated module.

1.3.2 Virtual Reality Systems for Fine Motor Skills

The high rate of atypical handedness and motor deficits among the children with ASD have been repeatedly reported [29, 106]. However, few technology-assisted systems are available for hand preference assessment and hand skill training of children with ASD. In this context, we developed a tablet game system and a haptic-gripper VR system that can motivate children with ASD to perform tasks requiring hand manipulations as well as record objective performance measures for hand preference and hand skill evaluation. Chapter 3 and 4 respectively present the development and application of these VR systems.

1.3.2.1 A Tablet Game for Assessing the Hand Movement

The tablet game system was designed to assess the hand usage of the player in movement manipulations. The games in the system can be played by one player using two hands or by two players each of whom using one hand. To play these games, the players should coordinate the manipulations of two hands (of one/two players), which required eye-hand coordination skill, hand movement skill, and interaction skills to communicate and cooperate with the partners.

We recruited four children with ASD and four TD children for a usability study. All the participants were right-handed. They were divided into four ASD-TD pairs. The paired participants first independently played the games using two hands. Then the paired participants played the games together on one tablet. They were required to use their dominant hands first and then use their non-dominant hands to play the same game.

The study results indicated that participants in both ASD group and TD group spent great efforts to perform non-dominant hand (left hand) manipulations in the one-player mode. However, participants with ASD showed strong positive relationship of the usage of the non-dominant hand and dominant hand, while only weak positive relationship was found among participants with TD. It might demonstrate that participants with ASD performed redundant or inefficient manipulations during playing the games. In addition, most of the participants preferred to play with a partner and on the average, they got higher scores for the same games in the two-player mode, which suggested that training tasks in the form of collaborative games would be more engaging and effective for children with ASD.

1.3.2.2 A Haptic-Gripper Virtual Reality System

The haptic-gripper VR system, calls Hg, provided the opportunities for assessing and practicing the hand motion control and grip control at the same time with a series of virtual handwriting-like tasks. It took the advantages of the haptic device to increase immersion and quality of task performance and thus had the possibility of enhancing the training achievements.

A usability study with six children with ASD and six TD children was conducted to analyze the impact of the system on the participants and the usefulness of the proposed performance metrics for assisting fine motor skill assessment. Each participant completed three sessions: a pre-test, an adaptive training session, and a post-test. The pre- and post-tests consisted of three virtual tasks and a Visual-Motor Integration (VMI) test to observe whether there were any differences in within system performance as well as in real-world tasks. The adaptive training session provided eight training tasks and would repeat some of these tasks based on the participant's performance.

The study results indicated medium to large relationships between several proposed performance metrics and the VMI scores, such as task score, grip force and position error, which suggested that the proposed metrics could be useful to quantify the fine motor skills, which might assist the fine motor skill assessment in an efficient and objective way. Participants in both groups achieved higher scores on both the VMI Motor Coordination test and virtual tasks, and performed more steadily and smoothly on the post-test tasks. In addition, features extracted from the performance data were found to be useful for distinguishing participants with ASD from TD participants with the accuracy up to 80%. These findings lend support to the promising potential of our system for fine motor skill analysis and training for individuals on the autism spectrum, which might expand the accessibility of efficient fine motor interventions.

1.3.3 Control Architectures for collaborative haptic virtual environments

Collaborative haptic virtual environments (CHVEs) enable haptic interaction between remote users who can perform collaborative tasks in the shared virtual space. The nature of CHVEs requires stable data synchronization of remote CHVE applications over network to achieve consistency in cooperation. Therefore, before developing the CHVE system, the performance of three control architectures for implementing the CHVE system, namely centralized control architecture, distributed control architecture and wave-variable-based control architecture, are tested and compared. With a simulated CHVE using MATLAB, these three control architectures were tested in terms of the position error and the force rendering under different network delays. The experimental results indicate that the centralized control architecture and the wave-variable-based control architecture have better performance with regard to the frequency response, the position error and the force rendering. Chapter 5 presents this work.

1.3.4 C-Hg: A Collaborative Haptic-Gripper Virtual Reality System

Most existing computer-assisted systems target only one specific skill deficit (e.g., social deficits) and ignore the importance of other skills (e.g., motor skills) in social interaction, which might hinder the application of learnt skills in real scenarios. The work presented in Chapter 6 seeks to bridge this gap by developing a Collaborative Haptic-Gripper virtual reality system (C-Hg) that can provide opportunities for practicing the fine motor skills and social skills at the same time and investigating how they relate to each other.

We conducted a usability study with 10 children with ASD and 10 typically developing (TD) children (age: 8-12 years) to observe the acceptability of C-Hg among the children with ASD, to explore the impact of the system on the fine motor skill of participants, and to investigate how fine motor skills relate to the social skills. One child with ASD was paired with one TD child based on age and gender. Each pair attended three sessions within 3-4 weeks. The first session and the third session included a pre/post-test and an individual training session, while the second session included two individual training sessions. We used a questionnaire to collect the participant feedback at the end of the post-test.

The study results indicated that this system was well designed to maintain the participant's interests on the training tasks as well as to provide social interaction opportunities. The results also presented significant performance improvements of participants in both individual and collaborative fine motor skill training tasks, and significant improvements of collaborative manipulations between partners. Participants with ASD were found to conduct more collaborative manipulations and initiate more conversations with their partners, suggesting more active collaboration and communication of participants with ASD in the collaborative tasks. Results support the potential of our C-Hg system for simultaneously improving fine motor and social skills, with implications for impacts of improved fine motor skills on social outcomes.

1.3.5 INC-Hg: An Intelligent Collaborative Haptic-Gripper Virtual Reality System

CVE has the potential to be an effective social skill training platform for children with ASD to learn and practice collaborative and communication skills through peer interactions. However, CVE usually requires time-matched and appropriate partners to guarantee productive interactions. In addition, the unrestricted conversations occurred during the peer-based interactions make it resource-intensive to manually analyze the communication patterns of the users. Therefore, in order to preserve the benefits of CVE-based platforms and mitigate some of the disadvantages, we developed an Intelligent Collaborative Haptic-Gripper System (INC-Hg) to provide an intelligent partner who can understand, communicate and haptically interact with the user. The INC-Hg operates in real time, and thus is able to perform collaborative training tasks at any time and at the user's pace. It is also able to record the real-time recognized conversation data and performance data, and therefore can greatly reduce the resource burden of performance analysis.

A preliminary usability study with 10 participants with ASD (age: 8-12 years) was conducted to investigate the acceptability of the intelligent agent among the children with ASD, to evaluate the agent's capability to interact with the user, and to assess the impact of the system on the participant performance. Each participant played a *Prize Claw* game twice and completed a survey to give their feedback. Participants with ASD reported that they liked to perform the collaborative tasks with the agent and enjoyed the haptic interaction with the agent, supporting system usability and tolerability within this population. Results also indicated that the system could classify the participant's utterances into five classes with the accuracy of 70.34%, which suggested the potential of INC-Hg to automatically recognize and analyze conversational content. The results also indicated high accuracies of the agent to initiate a conversation (97.56%) and respond to the participants (86.52%), suggesting the capability of the agent to conduct proper conversations with the participants. Compared to the results of human-to-human collaborative tasks, the human-to-agent mode achieved higher average collaborative operation ratio (61% compared to 40%), and comparable average frequencies for *Initiations* and *Responses* among the participants with ASD, which offered the preliminary support as well as areas of improvement regarding the agent's ability to respond to participants, work with participants to complete tasks, and engage in back-and-forth conversations, and suggested the potential of the agent to be a useful partner for individuals with ASD completing CVE tasks.

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CHAPTER 2

HAND-IN-HAND: A COMMUNICATION-ENHANCEMENT COLLABORATIVE VIRTUAL REALITY SYSTEM FOR PROMOTING SOCIAL INTERACTION IN CHILDREN WITH ASD

2.1 Abstract

Children with Autism Spectrum Disorder (ASD) often exhibit impairments in communication and social interaction, and thus face various social challenges in collaborative activities. Given the cost of ASD intervention and lack of access to trained clinicians, technology-assisted ASD intervention has gained momentum in recent years. In this chapter, we present a novel collaborative virtual environment (CVE) based social interaction platform for ASD intervention. The development of CVE technology for ASD intervention may lead to the creation of a novel low-cost intervention environment that will foster collaboration with peers and provide flexibility in communication. The presented Communication-Enhancement CVE system, Hand-in-Hand, allows two children to play a series of interactive games in a virtual reality environment by using simple hand gestures to collaboratively move virtual objects that are tracked in real-time via cameras. Further, these games are designed to promote natural communication and cooperation between the users via the presented Communication-Enhancement mode that allows users to share information and discuss game strategies using gaze- and voice-based communication. The results of a usability study with 12 children with ASD and 12 typically developing peers show that this system was well accepted by both the children with and without ASD, improved their cooperation in game play, and demonstrated the potential for fostering their communication and collaboration skills.

2.2 Introduction

Autism spectrum disorder (ASD), characterized by deficits in communication and social interaction together with restricted, repetitive and stereotyped patterns of behavior, represents a range of neurodevelopmental disabilities [1-3].

One in 68 children are diagnosed with ASD in the US [4, 5], with prevalence rates amongst school-aged children (6-17 years) increasing from 1.16% to 2.00% between 2007 and 2012 [6]. Many children with ASD have difficulty developing the social competence required for appropriately interacting with peers, which may lead to poor social-emotional reciprocity, misuse of verbal or non-verbal behaviors, and inappropriate relationships [7, 8]. Research has shown that compared to typically developing (TD) peers, children with ASD may experience greater loneliness and difficulties in developing satisfying friendships and social networks, even though they themselves expect social involvement [9, 10]. Cascading effects of these social challenges could also prevent children with ASD from living independently, limiting their opportunities and training resources across systems of care.

Although ASD is a life-long disorder with no known cure, several studies have shown that children with ASD can learn how to act in social situations when they can repeatedly practice specific scenarios [5, 11-16]. However, traditional educational interventions for ASD are costly, inaccessible and inefficient due to limited resources and poor motivations [17-20]. In recent years, computer-based interventions have shown potential due to their low-cost, their appeal to children with ASD, and their relatively broader access. Many children with ASD exhibit a natural affinity for computer technologies that leads to a higher level of engagement and fewer disruptive behaviors in computer-based interactions [20, 21]. In particular, virtual reality (VR) technologies allows children with ASD to actively participate in interactive and immersive simulated situations [22, 23]. Several VR-based systems have been developed to teach important living skills, such as driving skills [24], and social skills, to children with ASD, and results suggest that children were able to appropriately understand, use and react to virtual environments with the possibility of transferring theses skills to real life. Bernardini et al. designed a game, called ECHOES, where children with ASD could interact with an autonomous virtual agent and practice social communication skills through a touchable screen. Their results showed the positive impact of ECHOES environment on children with ASD [25]. Ke et al. examined the potential effect of a VR-based social interaction program on the interaction and communication performance of children with high-functioning autism and found improved social competence measures after the intervention [26]. Smith et al. tested the efficacy of a VR job interview training program for adults with ASD and indicated that VR training could be a feasible tool to improve job interview skills [27]. Kandalaft et al. investigated the feasibility of a VR social cognition training intervention for young adults with high-functioning autism and found positive effects of the VR intervention on theory of mind and emotion recognition [28]. While VR-based intervention is promising as indicated by the above-mentioned literature, it is difficult to implement complex flexible interaction similar to peer-based interaction within traditional VR-based paradigms. Recent evidence suggests that children can show improvements in learning, communication and sociability when working or playing collaboratively with others [29]. Traditional VR environments usually depend on preprogrammed, rigid interactions with virtual avatars or objects and thus do not scale up well for complex adaptive interaction. Collaborative virtual environments (CVE), on the other hand, address the shortcoming of the traditional VR environments and enable multiple users in distributed locations to interact freely with one another within a shared virtual setting using a computer network. They can navigate and control the shared virtual world as well as communicate (verbally or non-verbally) to share information [30] and thus can benefit from peer-based interaction. Considering these advantages of CVE over traditional virtual environment, we wanted to design a CVE for children with ASD to foster social interaction with the purpose of: (1) granting users active control over interactions that gives children with ASD an opportunity to interact with others in a simple and less stressful environment; and (2) supporting collaborative games that inspire participation of children with ASD in the interactive work and conversation.

CVEs in recent years have been employed to enhance social understanding or skills in children with ASD. Schmidt et al. developed a game-based learning environment for youth with ASD to learn computational thinking and social skills while working together to solve problems with virtual programmable robots [31]. Weiss et al. created the TalkAbout CVE program for children to grasp social conversation skills [32]. Cheng et al. developed a CVE, where students talked with a virtual teacher to learn social techniques in the context of social scenarios [33]. In another study, Cheng et al. also simulated several animated social scenarios in a CVE for children with ASD to enhance the understanding of empathy [34]. Stichter et al. allowed youth with high functioning autism (HFA) to engage in collaborative tasks (e.g., to build a restaurant) in a shared CVE, called iSocial [35]. Millen et al. designed a CVE, encouraging students with ASD to attend the participatory design activities [36]. Several other works used touch-based tablet with multiple inputs and responses for collaborative activities to provide face-to-face interaction among users [32, 37, 38]. For instance, Battocchi et al. used a puzzle game capable of enforcing collaboration on the tabletop to facilitate cooperative behaviors in children with ASD [38]. All these studies indicate the promise of CVE system on improving social competence for children with ASD. Building upon this impressive body of previous work, our system offers new contributions in providing opportunities for flexible and varying collaboration, enhanced communication and objective measurements of collaboration and communication.

In this chapter, we present the design and development of a novel CVE, called the Hand-in-Hand (HIH) Communication-Enhancement CVE system, for children with ASD. This system has the capability to support naturalistic social interaction, promote communication within game play, and gather objective data on user's performance and communication in real time (Figure 2-1). The primary contributions of the current work are two-fold: (1) to design a novel CVE platform, Hand-in-Hand (HIH), to promote collaborative game play in children with ASD, and (2) to test the system with a usability study with children with ASD and their TD peers. HIH is unique in the sense that it requires two children to dynamically simultaneously coordinate their hand manipulative actions to move the virtual objects that can be played with or without verbal and gaze contingent communication between the players. To our knowledge, no such systems exist at present.

The rest of chapter is organized as follows: Section 2.3 describes the system architecture of the HIH CVE system. Section 2.4 presents the details of the usability study followed by the results and discussion in Section 2.5. Finally, in Section 2.6, we summarize the contributions of the current work along with its limitations and future potential.

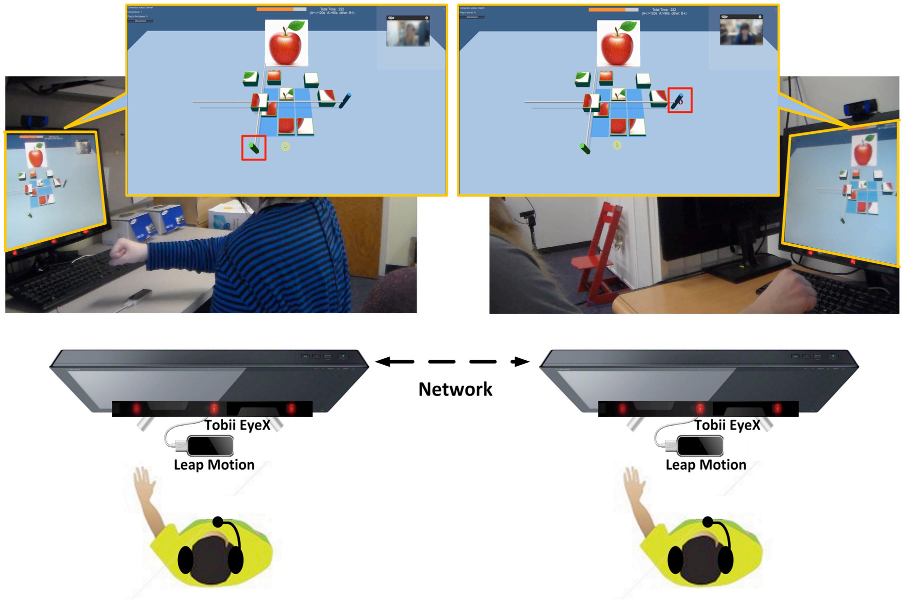


Figure 2-1. Two players wearing headphones in distant locations were playing the *Puzzle Game* in the HIH CVE system via the Leap Motion controller. They respectively controlled one virtual handle (marked by the red square) of the *Move Tool*. The Tobii EyeX tracker placed on the bottom of each monitor was used to track the eye gaze of each player on their respective monitor screen.

2.3 HIH CVE System Design

The primary goal of the HIH platform was to design a CVE platform that would provide opportunities for two players to collaboratively complete interactive games. It was designed specifically so that players situated in distant locations could use dynamic and simultaneous hand coordination to grab and move the virtual objects together. While puzzle games have been used in the literature to foster collaboration [38, 39], games requiring dynamic motor coordination have not yet been explored to the best of our knowledge. Although not a hallmark of the disorder, many children with ASD have deficits in motor control in addition to social interaction [40, 41] and HIH is designed to provide opportunities to teach both these skills simultaneously. An additional significant feature that distinguishes our puzzle games from others is that they require relatively complex cooperation between two players. That is, instead of collaboratively moving a puzzle piece toward the destination direction along the same axis, each player separately controls one movement direction (either horizontal or vertical), which is different from the destination direction. The combination of their movements leads to the puzzle piece being correctly placed. Thus, players need to think not only about their own movement, but also need to pay attention to their partner's operation to make sure their actions are coordinated.

Within the CVE, collaborative games were developed to foster flexible communication and interaction between the players. The whole system was built using the game development engine Unity3D [42] with three interacting modules and two data mangers (Figure 2-2). The *Application Module*, as the primary part of this system, manages the game connection and game execution. It allows data exchange and synchronization between two running applications on distant computers so as to support simultaneous manipulations of virtual objects by the two players in the same games. It also guarantees the proper functioning of games based on predefined logics. The *Communication Module* enables real-time video and audio communication between distant players and provides voice data for the *Application Module*. The *Eyetracker Module* obtains the player's gaze data in real time, which combined with the voice data are used to achieve gaze and voice contingent communication in games. The *Data Managers* record performance and conversation data of each player for offline analysis.

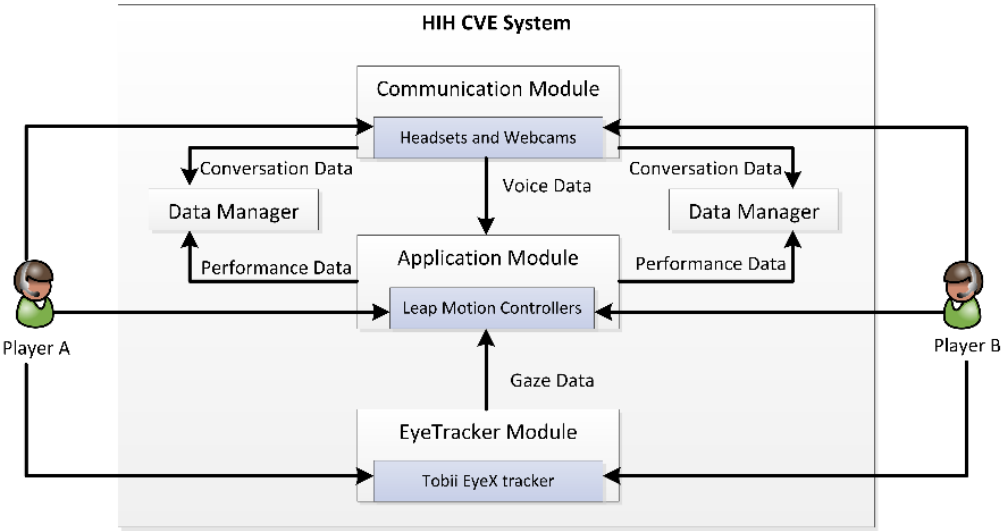


Figure 2-2.The HIH Communication-Enhancement CVE system architecture that includes three major modules and two data managers for each user. The hardware devices associated with each module are shown within the modules. The arrows with texts explain the data flow in this system.

Each player interacting with this system is equipped with one Leap Motion controller [43], a set of headset and webcam, and one Tobii EyeX tracker [44]. The Leap Motion device, which is a camera based user input system, can recognize the players' hand locations and gestures as the control signals to manipulate virtual objects in the CVE. The headset and the webcam are used for audio-visual communication, while the Tobii EyeX tracker acquires the gaze information of the players.

In subsequent sections, we discuss each part of the system in details to present the hardware, the software platform and implementation approaches for the design.

2.3.1 Application Module

Game design is the core of *Application Module*. The game type and logic can affect the behaviors and communication of the players. First, we considered the collaborative modes in order to promote interaction between the users. Considering that collaborative work always requires concerted intentions and actions among partners, the games were designed to move virtual objects collaboratively for a common objective. Additionally, the requirement for collaborative manipulation can be varied through different games. At the same time, we also wanted each player to equally contribute toward these movements. In order to facilitate this, we created collaborative tools that could help as well as force each player to make efforts in the collaborative manipulations. The collaborative tool that we designed had two handles, each of which was controlled by one player to move virtual objects. However, in order to make the use of the tool more natural, we further improved the virtual object manipulation capability of the users by allowing them to use their hand to virtually grasp the tool handles. We chose the Leap Motion controller, which can track one's hand in real-time, to enable hand control in the games. We believe that the use of such a device likely fosters the practice of realistic manipulation behaviors in players, such as grabbing and moving, which may be helpful for children with ASD. Finally, we designed a series of collaborative games played with the Leap Motion devices. These games were developed with the game development engine, Unity3D, because it could be easily integrated with the Leap Motion controller and support interactive game experience. Some virtual objects and pictures in the games were obtained from free online repositories, while others were developed with Autodesk Maya [45].

2.3.1.1 Leap Motion Controllers and Collaborative Tools

Leap Motion controller is a gesture-based interactive tool that allows players control tools in a more naturalistic way and feel more immersed within the games. This small device (3 × 1.2 × 5 inches) is easy to use by placing it in front of the player (Figure 2-1). When the player puts his/her hand above it within its detection range (approximately a field of view of 150 degrees and a range between 25 to 600 millimeters), it can track the 3D locations of hand and fingers and recognize the gestures with high speed and accuracy [46]. Two virtual collaborative tools, *Move Tool* (Figure 2-1) and *Collection Tool* (Figure 2-3, Figure 2-4), were developed with the Leap Motion controller application programming interface (API) that functioned based on the real-time hand data of the two players. To simplify the hand behaviors required for manipulating the tools, players only needed to learn three gestures: (1) close hand to grasp the handle; (2) open hand to release the handle; and (3) move hand to manipulate a virtual object using the handle. Once both players grab their handles and move their hands toward the same target, the tool is able to control objects in the CVE. For instance, when moving a puzzle piece to the correct location with the *Move Tool*, both players should first choose the same puzzle piece and then move it together by controlling one movement direction (horizontal or vertical direction) by each player. Without the help of the partner, puzzle piece cannot be chosen or moved. The *Collection Tool* also forces the players to cooperate, because the tool would not move or collect virtual objects unless both handles move consistently.

Collaborative tools combined with the Leap Motion device provide realistic manipulations as well as instant visual feedback of their operations. The states of handles (e.g., motion and orientation) reflect a player's actions and intention, and thus allows better understanding of their partner's operations and thus likely promotes better cooperation between the partners even in distant setting.

2.3.1.2 Collaborative Games Design

We designed three collaborative games in this work, which are called *Puzzle Games* (*PG*), *Collection Games* (*CG*) and *Delivery Games* (*DG*). These games were designed based on the following specifications: they should (1) be easy to learn and engaging for children; (2) be goal-oriented and time-limited to motivate active behaviors; (3) involve visuo-spatial collaborative activities, and (4) foster extensive interactions and communication.

All these games require two players to collaboratively move virtual objects to correct locations using collaborative tools within a certain period of time (5 minutes for *Puzzle Games* and 3 minutes for *Collection* and *Delivery Games*). Players score every time they successfully put one virtual object in the correct location. In the *Puzzle Game*, two players are required to put nine separate puzzle pieces together according to the provided target picture (e.g., the "apple" picture in Figure 2-1). The *Collection Games* (Figure 2-3) require two players to bring nine scattered toys to the collection areas with toy pictures. And, in the *Delivery Games* (Figure 2-4), two players should deliver several stars (at most seven stars) to some available destinations with different rewards (e.g., 4, 6 and 10 points) while avoiding moving through the red-striped "dangerous" areas. These games are the same games that we briefly discussed in [47] with one major exception – we have designed and integrated a *Communication-Enhancement* mode in the *Collection Games* and the *Delivery Games* to facilitate audio-visual communication opportunities between the players. Figure 2-5 shows the major modes for these games.

All of these collaborative games require simultaneous manipulations by two players in distributed locations. We used a server-client architecture for real-time data exchange and synchronization so as to maintain consistent game states on connected applications. The *serverApp* performs major game computation and control, while the *clientApp* only addresses the handle control and communication detection locally. The local data from *clientApp*, including client handle states, the voice and gaze data of the client player, are sent to the *serverApp* that performs the game logic, updates the game states based on the data of both applications and propagated updated data to the *clientApp* at a regular frequency (50Hz).

In the *serverApp*, several concurrent modes are chosen to implement the game logic based on different game specifications. The *Handle* mode is designed to map a player's manipulations to the states of the handles of the collaborative tools. The *Virtual_Objects* mode is designed to change the virtual objects' locations depending on the states of the collaborative tools. The *Score* mode is used to manage and display players' scores. The *Game_Timer* mode records the remaining game time, and the *Target* mode manages the targets' states (e.g., locations and numbers).

Except for these basic modes, the *Collection Games* have the *Display_Timer* mode to record the elapsing time for displaying one target, during which players are given at most 15 seconds to collect the target object. When players successfully collect the target object or the display time is out, the *Display_Timer* mode will reset the display time (15 seconds) and the *Target* mode will update the target by randomly showing a new target in one of the collection areas.

In addition, to promote audio-visual communication between the players, the *Collection and Delivery Games* require additional modes or states. Both games include the *Communication_Enhancement* mode to provide the communication opportunity for the players after one successful collection or delivery. The *Communication_Detection* mode detects if the players are talking and looking to each other, and the *Communication_Timer* mode allows at most 20 seconds' communication interval. During the communication interval, the game is paused and prompts "Look and Talk to your partner!" to encourage communication (Figure 2-3, Figure 2-4). When communication time is out or both players look and talk to each other, the game will resume and continue. Specifically, the *Collection Games* will add more targets as rewards for players to improve their scores as soon as both players start looking and talking to each other within the first 8 seconds. Players are thus encouraged to actively communicate with their partners.

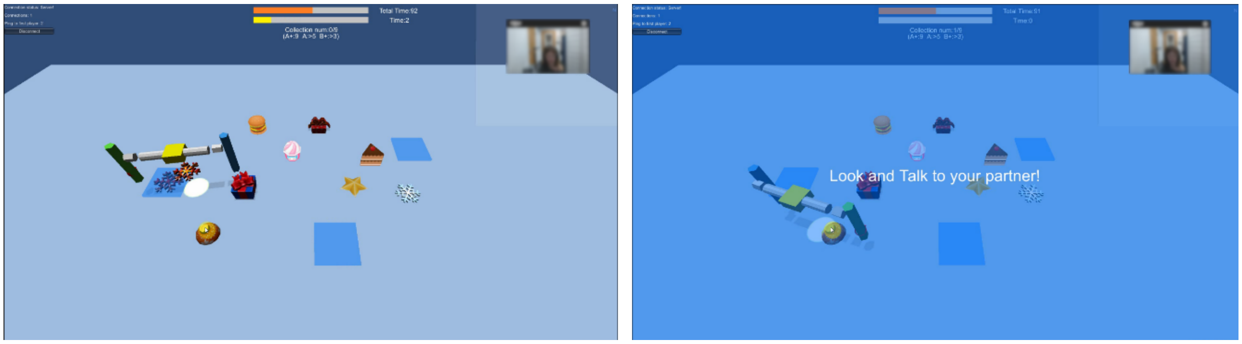


Figure 2-3. The *Collection Game* with Communication-Enhancement functionality. After players collect one toy (e.g., the red snowflake in the left picture) using the *Collection Tool*, the game is paused and gives a cue: "Look and Talk to your partner!" for players (as shown in the right picture).

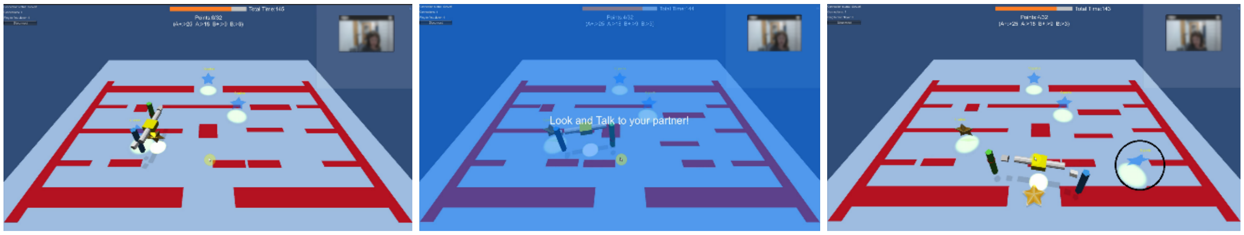
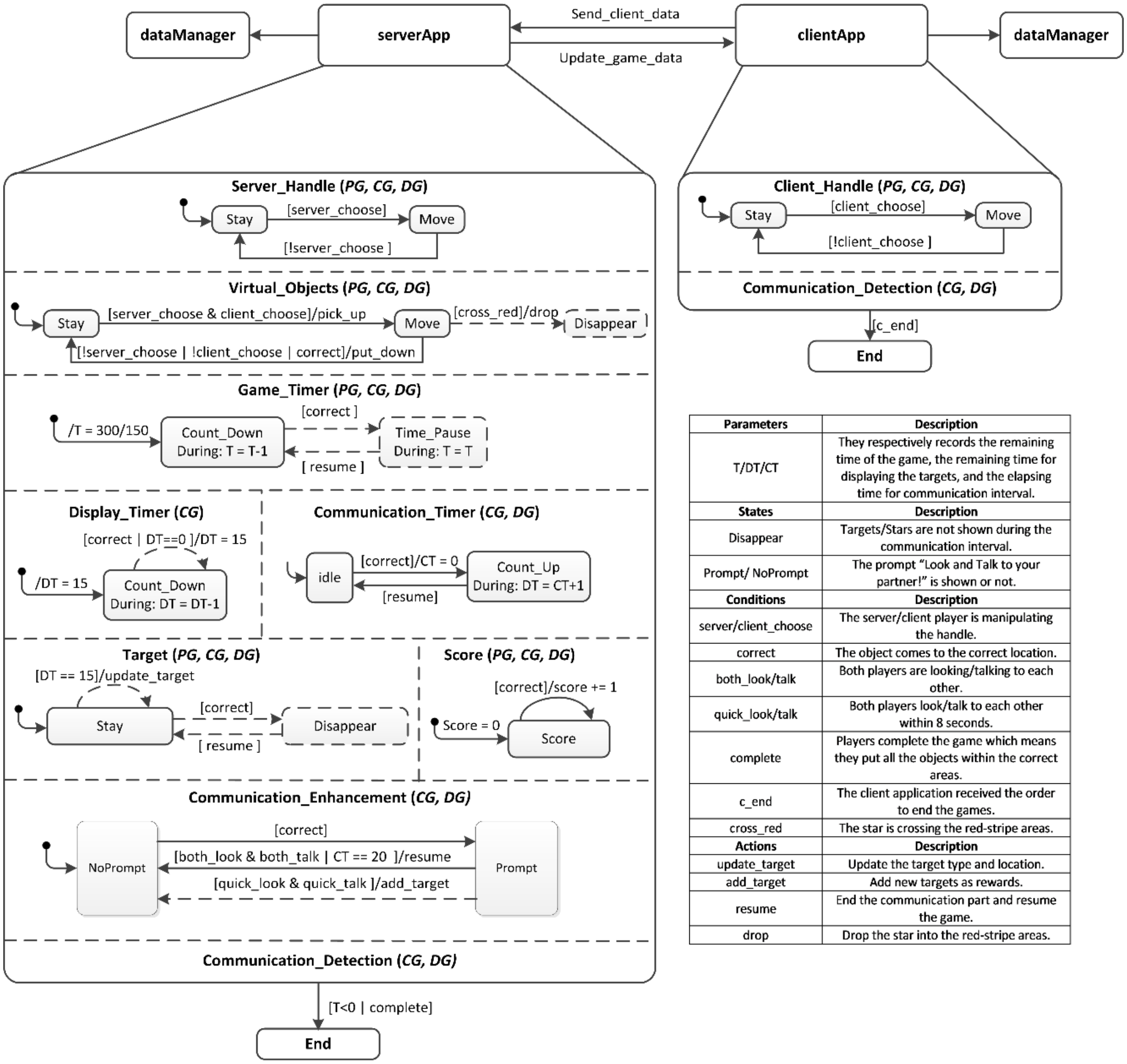


Figure 2-4. The *Delivery Game* with Communication-Enhancement functionality. After players deliver one star (e.g., the star delivered to the left target area in the left picture), the game is paused and gives a cue ("Look and Talk to your partner!") to players (as shown in the middle picture). If both players can quickly look and talk to each other, they will be rewarded with an additional target (e.g., the right target marked with black circle with 3 points in the right picture) near the starting point and thus they can have a chance to increase their scores.



Parameters	Description
T/DT/CT	They respectively records the remaining time of the game, the remaining time for displaying the targets, and the elapsing time for communication interval.
States	**Description**
Disappear	Targets/Stars are not shown during the communication interval.
Prompt/ NoPrompt	The prompt "Look and Talk to your partner!" is shown or not.
Conditions	**Description**
server/client_choose	The server/client player is manipulating the handle.
correct	The object comes to the correct location.
both_look/talk	Both players are looking/talking to each other.
quick_look/talk	Both players look/talk to each other within 8 seconds.
complete	Players complete the game which means they put all the objects within the correct areas.
c_end	The client application received the order to end the games.
cross_red	The star is crossing the red-stripe areas.
Actions	**Description**
update_target	Update the target type and location.
add_target	Add new targets as rewards.
resume	End the communication part and resume the game.
drop	Drop the star into the red-stripe areas.

Figure 2-5. The Statechart diagram showing major modes developed for implementing the collaborative games. Some modes are used in all the games, while some other modes (displayed by dashed line squares) are only needed in some games. The bottom-right table explains several elements displayed in the diagram.

2.3.1.3 Collaborative Strategies

To win these games, players have to talk and cooperate with each other. First, the game description only introduces the basic game rules and players need to figure out how to collaboratively work with their partners. For example, they are told that each player controls one handle, but they do not know which handle belongs to whom, which they need to find out either by trying out themselves or by discussing with their partners. During experiments, we found that many players tended to tell their partners which handle they should control and even how to control after they learnt the skill themselves.

Second, specific strategies can enhance information sharing and game-based discussion. In the *Puzzle Games*, players were sometimes confused about the partial pictures of the target and debated where the individual puzzle pieces should go. And because one puzzle piece can only be picked up when both players are manipulating the collaborative tool and each player controls one of the moving directions (either horizontal or vertical) of the puzzle piece, they have to first jointly determine which puzzle piece to move and where to put it. In one of the *Collection Games*, the target picture is only visible to one player, who should then share the information with the partner to make sure they move toward the same direction. In another *Collection Game*, two target pictures simultaneously appear in the game space. However, one of them is visible to one player, while the other one is visible to the other player. Two players thus may move toward two different targets if they do not discuss the target they see or the direction they want to move to. Manipulation conflicts are therefore likely to occur when there is little or no communication between the players. This was intentional, to implicitly encourage more information sharing which, in turn, could lead to more communication. In the *Delivery Games*, there are several paths to several destinations with different rewards. Two players should discuss which destination to deliver the star and which path to go. Additionally, these destinations are surrounded by several stationary or moving “dangerous” strips. Players thus need to discuss how to coordinate their movement orientation and speed in order to avoid these “dangerous” strips.

The introduction of the newly designed *Communication-Enhancement* mode provides a short interval for players to freely chat with each other during games. They talked about the game objectives, the skills needed to play the games, the next steps they should do, judged the partner’s performance, and so on during this short time interval.

2.3.1.4 The use of Gaze and Voice Data

The Communication Detection mode was designed to infer whether the two players were looking at each other and talking to their partners. This mode obtains gaze and voice data of each player in real time. As mentioned before, gaze data were obtained from the *EyeTracker Module*, while the voice data came from the *Communication Module*.

The software associated with Tobii EyeX tracker provides methods to check gaze in real time, which is useful to check whether player's gaze is within the region of interest (ROI) area. The live video feed of the partner is put at the top right corner of the screen in our games, which does not overlap with the other ROIs of the game. Once a player's gaze enters the top right corner, the player is judged to be looking at his/her partner.

Detection of talking between the partners was implemented by calculating the volume and fundamental frequency of the sound coming from the microphone. The volume reflects the loudness of a sound which is proportional to the amplitude of the sound wave, while the fundamental frequency refers to the vibration of a sound. When people talk, the volume and domain frequency change significantly compared to the silent situation. The volume and fundamental frequency of a sound can be computed by

$$volume = 20 \times log_{10}\left(\frac{rmsValue}{refValue}\right) \tag{2-1}$$

$$fundamental_{frequency} = N_{max} \times freqResolution \tag{2-2}$$

where $rmsValue$ represents the root mean square (RMS) of sound amplitude, $refValue$ is the RMS value for 0 dB, $N_{\max}$ is the index of maximum amplitude element, and $freqResolution$ represents frequency resolution of the sound.

The Unity3D software functions, *GetSpectrumData* and *GetOutputData*, allow developers to access the information about the amplitude and frequency of audio data, which makes it possible to compute the volume and dominant frequency of sound from the above equations. From our previous study [47], we collected voice samples from the participants to analyze the range of volumes and dominant frequencies of their voices to design thresholds for the current study. The volume threshold was set as ≥30 dB and the fundamental frequency threshold was set as 170 Hz-300 Hz (the upper limit was set to avoid noise). A player is judged to be talking when both his/her voice volume and frequency fall within these threshold ranges.

2.3.2 Communication Module and EyeTracker Module

The *Communication Module* supports video and audio communication between players by using the software Skype [48]. When using our system, one player makes a video call to his/her partner and builds the communication channel, through which players can discuss strategies for playing games and sharing information in real time. Each player's voice is recorded through the microphone in real time, and utilized in the *Communication_Detection* mode to detect if the player is talking.

The *EyeTracker Module* obtains player's gaze information with the Tobii EyeX eye tracker, which is capable of tracking the gaze point as player's eyes scan the screen. It is placed on the bottom of the monitor screen and plugged in the Unity to transmit gaze data to the *Communication_Detection* mode for online "look" detection.

2.3.3 Data Managers

Data managers were developed to save the objective gaming data as well as the conversations between players for offline analysis. Gaming data, such as completed pieces, cooperation ratio and total play time, can indicate a player's performance and cooperation. Recorded audios of conversations between two players are transcribed verbatim and used to analyze communication between the players (Table 2-1).

Table 2-1. Metrics of performance and communication.

Metrics	**Description**
Completed pieces (/minute)	The number of puzzle pieces that matched the target in one game per minute.
Cooperation ratio (%)	The time of collaboratively manipulating the puzzle piece divided by total manipulating time.
Total play time (s)	The time of playing one game (the maximum allowed play time of *Puzzle Game* was 300s).
Back-and-forth sentences(/minute)	One back-and-forth sentence was defined as one player spoke and his/her partner responded.
Words count of one player (/minute)	The total number of words that each player spoke in one game divided by the total play time.

2.4 Usability Study

The goal of this study was to conduct a preliminary evaluation of this novel system regarding its ability to foster collaborative activities among participants. We collected preliminary pilot data regarding collaborative actions to assess change within our small pilot sample and validate the capacity of the system to address main hypotheses.

2.4.1 Participants

We recruited 12 children with ASD and 12 TD children for the usability study of the HIH CVE systems with and without the *Communication_Enhancement* mode. One child with ASD was paired with one TD child based on age and gender to form a group (i.e., 12 groups in total). The reason for not creating the ASD-ASD pair is that it is more common for children with ASD to interact with TD peers in daily life, and the goal of ASD intervention includes improving the relationships of children with ASD with their TD peers.

We conducted two studies with HIH CVE system. In Study 1 we tested the system without the *Communication_Enhancement* mode. In Study 2, we tested the system with the *Communication_Enhancement* mode. The studies were approved by the Vanderbilt University Institutional Review Board. Both sets of experiments were conducted after obtaining the assent of the participants, consents from their caregivers and under the supervision of trained ASD therapists and experimenters. The parents of the participants first completed ASD symptom measurements: the Social Responsiveness Scale (SRS) [49] and Social Communication Questionnaire (SCQ) [50]. Afterwards each participant went to separate experimental rooms and played games together within the shared CVE through the local area network as shown in Figure 2-1. Table 2-2 presents the detailed information of participants. All participants spoke with flexible phrase speech and could complete all aspects of game play without adult prompting or support.

Table 2-2. Participant characteristics.

Participants	Study 1		Study 2	
	ASD (n=6)	**TD (n=6)**	**ASD (n=6)**	**TD (n=6)**
	Mean (SD)	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**
Age (years)	12.38 (2.60)	12.60 (2.66)	12.12 (3.59)	13.15 (3.77)
SRS-2 total raw score	108 (17.13)	41 (24.11)	105.8 (13.4)	12.5 (6.87)
SRS-2 T-score	80.5 (7.80)	53.33 (9.27)	81 (5.94)	42.5 (3.45)
SCQ current total score	19.7 (11.35)	7 (8.70)	13.5 (4.54)	1.33 (1.25)

2.4.2 Procedure

At the beginning of each experiment, experimenters explained the procedure and devices (e.g., Leap Motion controller, Tobii EyeX tracker, camera, and headset) to the participants and taught them how to interact with the Leap Motion Controller. Participants in separate rooms then completed individual calibration of their eye tracking device, and built an audio and video communication channel with the partner via Skype.

The whole experimental procedure is described by the simplified flowchart in Figure 2-6. Two running applications were first connected via the IP addresses. Then, participants practiced handle operations in an independent practice game under the guidance of the experimenters. As players were supposed to control handles in all games, they repeatedly practiced grabbing, moving and releasing one handle in this practice game. Until they got used to the handle controls they were not allowed to enter the next session, “Game Introduction,” that presented the rules of each game with illustrative images and words.

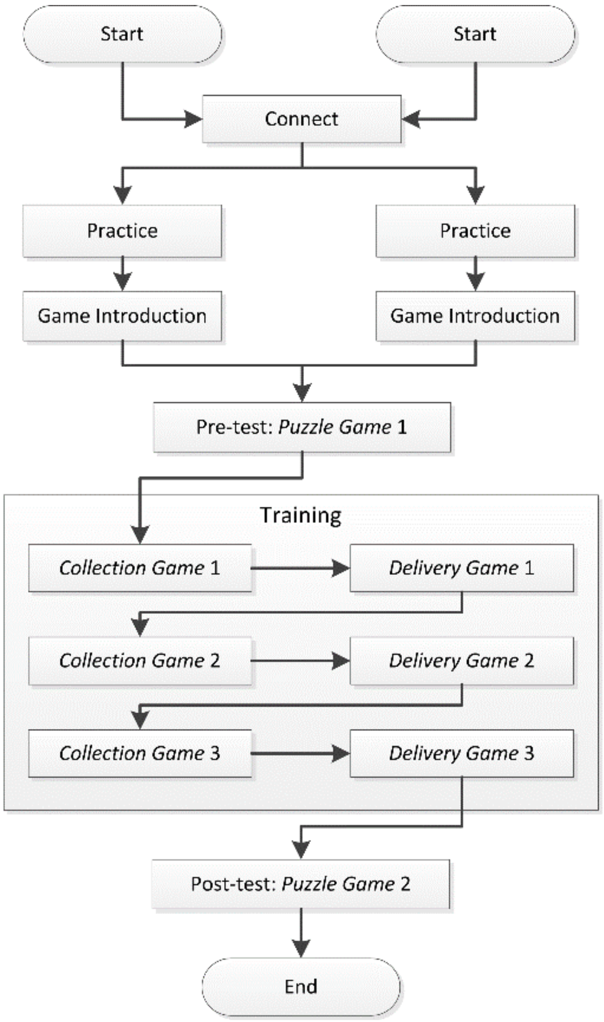


Figure 2-6. Flowchart of the experimental procedure.

After both participants got familiar with playing the collaborative games, they entered the game session which consisted of eight games. Each game was automatically loaded one by one based on a pre-defined order. Participants were required to collaboratively complete these games without the help or intervention of the experimenters or therapists. *Puzzle Games* were played in the pre- and post-test to assess the change of participant performance and communication. The *Training* session consisted of three *Collection Games* and three *Delivery Games* to enhance social understanding and collaborative skills of the participants. These training games were different from one another and became increasingly more difficult requiring progressively more discussion between participants. In addition, the *Communication-Enhancement* mode slowed down the pace of the game and created more opportunities for communication. Table 2-3 includes the main configuration differences of all the games. Diverse types of games were intended to keep participants engaged and motivated to negotiate with their partners. After completing all games, each participant filled out a questionnaire to give feedback in terms of engagement, performance and communication, as well as advice for improving the system. Before they left, they each received gift cards as compensation.

Table 2-3. Game configuration differences.

Games	Differences
Puzzle Game 1	Target picture is “Lemon”.
Puzzle Game 2	Target picture is “Apple”.
Collection Game 1	Every time, the target picture is visible to both players.
Collection Game 2	Every time, the target picture is only visible to one player but invisible to the other one.
Collection Game 3	Every time, two target pictures simultaneously appears, each of which is only visible to one of the players.
Delivery Game 1	Obstacles move along the horizontal or vertical direction.
Delivery Game 2	Obstacles spin around fixed centers.
Delivery Game 3	Obstacles move in several complex manners.

2.5 Results and Discussions

Here we first present the system validation results to demonstrate that the HIH Communication-Enhancement CVE system functioned robustly and stably. Then we give the usability study results from two aspects: participant feedback (subjective) and participant performance (objective), and also compare the results of Study 1 and Study 2 to show the advantages of HIH Communication-Enhancement CVE system in fostering collaborative gameplay skills and social communication in children with ASD.

2.5.1 System Validation Results

The nature of CVE requires stable data exchange and synchronization in real time. We thus first evaluated the network communication performance of this system by analyzing the rate of RPCs (Remote Procedure calls). RPCs in Unity3D enables data transmission to remote machine and the RPC rate can indicate the data transmission rate over the network. Six tests were conducted on two computers that had 3.7 GHz processors (8 GB and 16GB of RAM) and NVIDIA Quadro K600 GPUs (60 Hz refresh rate). The results for each game are shown in Table 2-4. The average network communication throughput of the server and the client for all the games was around 50 Hz, which was the same as the pre-defined transmission rate. This rate is sufficiently fast to avoid latency in connected games.

We also measured the accuracy of the eye gaze detection in the ROI to make sure that the *Communication-Detection* mode functioned as designed. We sought the help of 6 volunteers to participate in a measurement task that asked each of them to look at the ROI area for 10 times for 10s as well as the non-ROI area for 10 times for 10s. The accuracy of gaze detection for each volunteer is showed in Table 2-5. It was found that the eye gaze detection had an average accuracy of 91.26% for the ROI area and 99.61% for the non-ROI. Since the detected behavior "looking at the partner" was a continuous action, more than 90% accuracy were deemed acceptable for the system.

Table 2-4. Test results of data transmission rate (Hz)

Games	**Server**		**Client**	
	Mean	**SD**	**Mean**	**SD**
Pre-test	50.19	0.30	50.20	0.31
Training 1	50.02	0.01	50.02	0.01
Training 2	50.05	0.41	50.06	0.41
Training 3	50.02	0.01	50.05	0.06
Training 4	50.02	0.01	50.05	0.06
Training 5	50.29	0.63	50.30	0.62
Training 6	49.84	0.43	50.02	0.01
Post-test	50.20	0.68	50.21	0.68

Table 2-5. Accuracy of eye gaze detection (%)

Volunteers	**ROI**		**Non-ROI**	
	Mean	**SD**	**Mean**	**SD**
1	89.78	0.52	99.56	0.14
2	95.46	0.47	100	0
3	87.76	0.43	98.94	0.29
4	84.54	0.69	100	0
5	92.42	0.43	99.82	0.06
6	97.6	0.43	99.32	0.22

2.5.2 Participant Feedback

We collected participant feedback about using the system with a questionnaire including 10 questions. In Table 2-6, we present these questions associated with the answers of the participants from the two studies to show and compare participant feedback in using the HIH CVE systems with and without the Communication-Enhancement mode.

Table 2-6. Participant feedback from two usability studies.

Question: 1-6	**Study 1**				**Study 2**			
	ASD (n = 6)		**TD (n = 6)**		**ASD (n = 6)**		**TD (n = 6)**	
	Mean (Min/Max)	**SD**	**Mean (Min/Max)**	**SD**	**Mean (Min/Max)**	**SD**	**Mean (Min/Max)**	**SD**
1. Like the games?	3.67 (1/5)	1.25	3.33 (1/4)	1.11	4.67 (4/5)	0.47	4.33 (4/5)	0.47
2. Did you do well?	4.00 (2/5)	1.00	3.33 (1/4)	1.11	4.33 (4/5)	0.47	3.83 (2/5)	0.90
3. Did partner do well?	3.50 (2/5)	1.12	3.17 (1/4)	1.07	4.50 (4/5)	0.50	4.67 (4/5)	0.47
4. Important to talk?	4.00 (2/5)	1.00	4.33 (3/5)	0.75	4.83 (4/5)	0.37	4.67 (4/5)	0.47
5. Important to cooperate?	4.83 (4/5)	0.37	4.83 (4/5)	0.37	4.50 (4/5)	0.50	4.83 (4/5)	0.37
6. Easy to work together?	3.50 (1/5)	1.38	2.83 (1/5)	1.34	3.33 (1/5)	1.37	3.67 (3/5)	0.75

Question: 7-10	**ASD-TD in Study 1**	**Choices**	**ASD-TD in Study 2**
7. How often did you talk?	10 (5/5)	"Very often".	10 (5/5)
	2 (1/1)	"Only when I needed".	2(1/1)
	0	"Very little".	0
8. Which was most useful to learn how to play?	6 (3/3)	"Talking with my partner".	9 (4/5)
	1 (0/1)	"Reading game instructions".	2 (1/1)
	5 (3/2)	"By trying several times".	1(1/0)
9. Which was most useful to win?	11 (5/6)	"Working closely with my partner".	10 (4/6)
	1 (1/0)	"My personal performance".	1(1/0)
	0	"Understanding the game rules".	1(1/0)
10. Did you play better?	3 (2/1)	"We played better by the end".	11(5/6)
	8 (3/5)	"Stayed the same".	1(1/0)
	1 (1/0)	"We played worse".	0

The first six questions used a five-point Likert scale. The answers for these questions indicated that participants in both studies liked the games (Q1: Mean ≥ 3.67), played well in these games (Q2: Mean ≥ 3.33, Q3: Mean ≥ 3.50), confirmed the importance of communication (Q4: Mean ≥ 4) and cooperation (Q5: Mean ≥ 4.5), and felt it was not hard to work with their partners in the games (Q6: Mean ≥ 2.83).

In addition, participants in Study 2 gave more positive feedback for most of these questions compared to participants in Study 1 ($\text{Mean}_{\text{Study2}} = 4.35 > \text{Mean}_{\text{Study1}} = 3.78$). In Q1, the participants in Study 2 showed considerable interest in these games ($\text{Mean}_{\text{ASD}} = 4.67$, $\text{Mean}_{\text{TD}} = 4.33$) compared to those in Study 1 ($\text{Mean}_{\text{ASD}} = 3.67$, $\text{Mean}_{\text{TD}} = 3.33$). In Q2, the participants in Study 2 ($\text{Mean}_{\text{ASD}} = 4.33$, $\text{Mean}_{\text{TD}} = 3.83$) gave a slightly higher score for self-evaluation than those in Study 1 ($\text{Mean}_{\text{ASD}} = 4$, $\text{Mean}_{\text{TD}} = 3.33$). In Q3, the participants in Study 2 also gave a higher score for their partners' performance ($\text{Mean}_{\text{ASD}} = 4.50$, $\text{Mean}_{\text{TD}} = 4.67$) than those in Study 1 ($\text{Mean}_{\text{ASD}} = 3.5$, $\text{Mean}_{\text{TD}} = 3.17$). To consider Q2 and Q3 together, we found that the participants in Study 2 thought more highly of their partners ($\text{Mean}_{\text{Q3}} > \text{Mean}_{\text{Q2}}$), which may indicate social niceties to appreciate one's partner's work that was not seen in Study 1 ($\text{Mean}_{Q3} < \text{Mean}_{Q2}$). In Q4, the participants in Study 2 understood the importance of communicating with partners better ($\text{Mean}_{ASD} = 4.83$, $\text{Mean}_{TD} = 4.67$) compared to those in Study 1 ($\text{Mean}_{ASD} = 4$, $\text{Mean}_{TD} = 4.33$). In Q5, all participants gave a score as high as "4" or "5" about the importance of cooperation. In Q6, all participants except for the TD ones in Study 1 felt it was easy to work together with their partners. From our observation, one challenge in cooperation was to correctly or quickly respond to partners' questions or commands, which sometimes was harder for some participants (most were participants with ASD). For example, when one participant asked, "Which object do you want to do next?", his/her partner only answered, "That one," instead of specifying the object. However, the introduction of *Communication-Enhancement* mode in the current system increased opportunities for communication and allowed participants to do timely information sharing and understand the partners' ideas and feelings, which we thought led to better game experience in Study 2.

The last four questions were choice questions and participants' answers were counted and shown in the form of "Total number (ASD number/TD number)" in Table 2-6. The answers for these questions indicated that most participants believed that they talked "very often" in the games (Q7: 20 out of 24), the most useful way to learn how to play was to talk with their partners (Q8: 15 out of 24), the most useful way to win was to work closely with their partners (Q9: 21 out of 24) and they played better (Q10:14 out of 24).

However, several questions were answered differently by the two study participants. For example, in Q8, most participants in Study 2 (9: ASD = 4, TD = 5) thought "talking with my partner" was the best way to learn how to play the games. However, in Study 1, six participants (ASD = 3, TD = 3) chose "talking with my partner", while there were still five participants (ASD = 3, TD = 2) chose "by trying several times". The results suggested that participants in Study 2 that used the system with *Communication-Enhancement* mode might have increased information sharing and game related discussions. In Q10, most participants in Study 2 (11: ASD = 5, TD = 6) felt they played better at the end, while fewer participants in Study 1 (8: ASD= 3, TD = 5) felt the same. The results were consistent with the performance results (discussed later in detail), because participants in Study 2 completed more puzzle pieces (increased by 1.27 per minute) than those in Study 1 (increased by 1.03 per minute).

2.5.3 Participant Performance

We conducted statistical analyses of participant game performance and communication in pre- and post-test. Note that the pre- and post-test games (*Puzzle Games*) were different from the training games in terms of game rules, objectives and use of collaborative tools to avoid habituation effect as well as to observe generalizability of the training. We compared the performance and communication metrics in the pre- and post-test using the two-tail Wilcoxon signed-rank test (alpha = .05) [51] and simultaneously evaluated the effect size via Cohen's d [52]. Since normality of this small sample (N = 6 pairs for each study) could not be assumed we used the Wilcoxon signed-rank test to analyze the data. Since this test produces a conservative result as compared to t-tests, we believe that this is the right approach because it will not overstate the effect.

Table 2-7 and Table 2-8 present the results for Study 1 and Study 2, respectively. None of the metrics except for the "cooperative ratio" of Study 2 showed statistically significant improvements (*W* = 0, *p* = .0313, |*d*| = 1.5394) between pre- and post-test. However, participant performance improved after the training session, sometimes with large effect size, considering the increased number of completed puzzle pieces, increased cooperation ratio and reduced total play time. Most of the participants (except for TD participants in Study 1) also spoke more in the post-test.

Table 2-7. Participant performance comparison in study 1.

Variables	**Pre-test**		**Post-test**		**Diff.**	***W***	***p*-value**	**|*d*|**
	Mean	SD	Mean	SD				
Completed pieces (/minute)	1.12	0.78	2.15	1.34	1.03	1.5	.0938	0.9390
cooperation ratio (%)	53.38	16.76	60.51	17.88	7.13	3	.1563	0.4110
Total play time (s)	288	25	224	65.11	-64	10	.1250	1.2890
Word count of participants with ASD (/minute)	34.21	30.77	36.53	26.64	2.32	8	.6875	0.0804
Word count of TD participants (/minute)	38.44	13.75	35.30	15.54	-3.14	15	.4375	0.2142
Back-and-forth sentences (/per minute)	3.71	2.00	2.82	1.76	-0.89	13	.1875	0.4671
Aggregate score	1.12	0.50	1.52	0.88	0.40	3	.1563	0.5649

Table 2-8. Participant performance comparison in study 2.

Variables	**Pre-test**		**Post-test**		**Diff.**	***W***	***p*-value**	**|*d*|**
	Mean	SD	Mean	SD				
Completed pieces (/minute)	1.18	0.86	2.45	1.48	1.27	1	.0625	1.05
Cooperation ratio (%)	36.98	22.92	68.61	17.87	31.63	0	.0313*	1.5394
Total play time (s)	289	21.25	242	85.11	-47	9	.2500	0.7604
Word count of participants with ASD (/minute)	28.65	19.59	33.66	17.24	5.01	7	.5625	0.2714
Word count of TD participants (/minute)	35.91	36.87	52.62	26.23	16.71	3	.1563	0.5224
Back-and-forth sentences (/per minute)	3.73	3.54	6.00	2.88	2.23	3	.1563	0.7033
Aggregate score	1.12	0.70	2.02	1.08	0.90	2	.0938	0.9857

To compare the cooperation performance of participants in two studies, we found that participants in Study 2 achieved more improvements. First, participants in Study 2 increased the number of completed puzzle pieces by 1.27 per minute (*W* = 1, *p* = .0625, |*d*| = 1.05 (large effect size)), while the increases in

Study 1 were 1.03 per minute ($W = 1.5$, $p = .0938$, $|d| = 0.9390$ (large effect size)). In addition, we found a statistically significant difference and a very large effect size regarding the cooperation ratio of participants in Study 2 ($W = 0$, $p = .0313$, $|d| = 1.5394$). Participants in Study 2 cooperated more efficiently by the end with an increase of 31.63%, compared to only 7.13% increase in Study 1 ($W = 3$, $p = .1563$, $|d| = 0.4110$ (small effect size)). The results suggested that participants in Study 2 using the system with the *Communication-Enhancement* mode cooperated and played better after the training session as compared to the participants in Study 1.

The total play time could partially reflect the difficulty of the games for the participants. However, since participants were given enough time (at most 300 seconds) to complete the games, they were not in a hurry. Sometimes, participants would like to talk for a while and then manipulate the puzzle pieces. The participants in both studies spent less play time in the post-test (Study1: $W = 10$, $p = .1250$, $|d| = 1.2890$ (large effect size); Study 2: $W = 9$, $p = .2500$, $|d| = 0.7604$ (medium effect size)).

To compare the communication of participants in these two studies, we found that participants in Study 2 communicated more frequently than those in Study 1 with regard to the back-and-forth sentences (full sentences and phrases). We counted the number of back-and-forth exchanges to assess how often they communicated in the games. We can see that communication between paired participants in Study 2 was enhanced by 2.27 per minute ($W = 3$, $p = .1563$, $|d| = 0.7033$ (medium effect size)). On the contrary, communication was decreased by 0.89 per minute in Study 1 ($W = 13$, $p = .1875$, $|d| = 0.4674$ (small effect size)). We also counted the words each participant spoke in the games. Though participants with ASD in Study 2 spoke words in a low level (pre: 28.65 words/minute; post: 33.66 words/minute) compared to those in Study 1 (pre: 34.21 words/minute; post: 36.53 words/minute), they still spoke more words (increasing by 5.01 words/minute) than those in Study 1 (increasing by 2.32 words/minute). Particularly, word count for TD participants in Study 1 decreased by 3.14 per minute, but increased substantially by 16.71 per minute in Study 2. These results showed that participants in Study 2 who used the system with the *Communication-Enhancement* mode were more likely to communicate with their partners by the end.

To further understand the performance results, we also calculated aggregate scores that integrated four performance measures, which were completed pieces, cooperation ratio, total play time and back-and-forth sentences. The data for each measure were first normalized using Min-Max scaling method, and then summed together to generate the final aggregate scores (range: 0-4). We observe that in both studies, participants achieved the same aggregate score (1.12) on average in the pre-test. However, participants in Study 2 got a higher score in the post-test ($W = 2$, $p = 0.0938$) characterized by the large effect size ($|d| = 0.9857$). The results may indicate that participants in Study 2 improved more with respect to cooperation and communication.

2.5.4 Preliminary Analysis of Conversations

We analyzed the conversation of the participants offline to understand whether they had any change in conversation between pre- and post-test. We divided the content of the conversation into two groups: game-oriented conversation and social conversation.

Game-oriented contents included sharing of game information and virtual object manipulation directives, which were necessary to accomplish the game objectives. Game information sharing occurred in two ways: (1) spontaneous information sharing and (2) question-and-answer. As participants could not directly observe the operations of their partners, they generally actively told their partners of their intentions and actions, such as “I have my hand on the handle”, “Wait, I’m trying to grab it”, “I think we need to take the piece out”, “This time is an apple”, “You are supposed to grab the green thing” and so on. Additionally, participants would inquire information from their partners, such as “take this one?” “Can you describe to me what you see? Because I can’t see your circle.” “Which piece would you want to go first?” “Where should it go?” and so on. Manipulation directives, like “go down”, “one more up”, “go and grab it” and “put this right here” happened frequently in their conversations, which reflected the embedded information sharing requirements of the designed game rules. We found that sometimes one of the paired participants would take the role of a “leader” to carry out the manipulation directives.

Social contents contained social information sharing and evaluations of partners. Some participants, including those with ASD, introduced themselves to their partners during the game. Some also discussed the games they played in their daily lives. In addition, participants would encourage their partners or praised their good performance in the games. For example, when they completed a game, they often said “We did it”, “Perfect”, “Good job” or “We are doing good”, and their partners always gave similar responses. At the beginning of a game, they would say “I bet we can get this time”, “We will do a good job” or “We can win this time if we work together as a team.” During the game, they would say “that’s good”, “We get it so right,” or “Let’s do this, bro. You are my man”. Sometimes they even joked about foolish actions, such as “you are not very good at this” and “You talk about like you making pizza”.

Through the conversation analysis, we found that although some participants would react slowly or describe things less accurately, they could be encouraged and promoted to improve their behaviors or share information with their partners. It appears that these collaborative games have the potential to provide a spontaneous communication space, which encourage conversations in a natural way.

2.6 Conclusion and Future Work

This chapter presents the development and evaluation of the Hand-in-Hand (HIH) Communication-Enhancement CVE system, which can provide a naturalistic social interaction platform for children with ASD and their peers, increase the opportunities for communication and cooperation within the collaborative games and collect quantitative data regarding collaborative and communicative performance of the participants. The usability study tested the acceptability of the system among children with ASD and obtained a preliminary assessment of the system. Results showed that participants enjoyed the collaborative games presented by this system and cooperated progressively better in these games. They also emphasized the importance of communication and cooperation with their partners in order to win these games. The *Communication-Enhancement* mode facilitated the spontaneous conversations between participants and performance analysis demonstrated that participants communicated more frequently with their partners by the end. In addition, we found that participants could be positively influenced by their partners in the process of playing these games. For instance, when one participant with ASD could not correctly answer his/her partner's question ("Where will the present go?"), the partner raised a new question ("The left area, middle area, or the right area?"); then the child with ASD could understand how to answer and replied, "The right one." These spontaneous conversations could help children with ASD practice verbal behaviors in a natural and visual way. We believe that the results of this usability study indicate a need for a fully-powered intervention study in the future to critically assess the intervention effect due to this novel system.

In the future, the HIH Communication-Enhancement CVE system will be further improved to support more naturalistic collaborative gameplay platform. We are now working on designing the CVE with the haptic interfaces that is able to produce physical feedback to the user. We expect the haptic CVE system could increase the sense of cooperation between partners. Additionally, more participants are needed in the future for the user study to assess the practical value of the system for children with ASD. In order to explore the influence of the system on the communication ability of the participants, we plan to continue with the analysis of the participant conversations in terms of the game-oriented content and the social content and perform a statistical analysis of the change in the content of the conversation.

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CHAPTER 3

A TABLET GAME SYSTEM TO ASSESS THE HAND MOVEMENT IN CHILDREN WITH ASD

3.1 Abstract

The high rate of atypical handedness and motor deficits among the children with Autism Spectrum Disorder (ASD) have been repeatedly reported. Recently, tablet-assisted systems are increasingly applied to ASD interventions due to their potential benefits in terms of accessibility, cost and the ability to engage many children with ASD. In this chapter, we propose the design of a tablet game system to assess the hand usage in movement manipulations of children with ASD. To play the games designed in this system, it requires good eye-hand coordination, precise and quick hand movements and cooperation with partners. The games can be played by one player using two hands or by two players each of whom using one hand. We present the system design and a small preliminary usability study that verified the system functionality in recording objective performance data for offline analysis of the hand usage of the players. Results showed that the proposed system was engaging to children with ASD and their TD (i.e. typically developing) peers, and could induce collaborative activities between them. The system was also shown to efficiently evaluate the usages of the dominant hand and the non-dominant hand of the users. We found that children with ASD showed different patterns of hand usage behaviors from the TD participants when using this system.

3.2 Introduction

Autism spectrum disorder (ASD), characterized by deficits in communication and social interaction, consist of a range of neurodevelopmental disorders [1]. Although not considered as the core symptoms of ASD, motor deficits and atypical handedness have been documented in a number of reports [2-5]. Several studies have shown higher incidence of non-right-handedness (including left handedness and ambiguous handedness) in children with ASD as compared to their typically developing (TD) peers [6, 7]. Handedness, as an indication of cerebral lateralization, suggests the link between the development of the dominant hemisphere and functional skills [8]. Generally, the left hemisphere is predominant in motor and language skills. A growing number of literature has suggested that non-right-handedness is associated with several disorders (e.g., language disorders, developmental learning disorders and poor motor functioning) [5, 9, 10]. In addition, children with ASD have been found to display a dissociation of hand preference and skill such that they prefer to use the hand which is less skilled [11, 12].

Handedness is always assessed by handedness measure tests, such as the Almli Handedness Assessment [13] and the Hand Preference Demonstration Test [14], or questionnaires. However, these methods usually involve laborious work or subjective evaluation. The technology-assisted systems applied in multiple types of ASD interventions [15, 16] suggest the potential use of these systems as the novel intervention platforms to engage children with ASD in an interesting, low-cost, efficient and objective intervention environment with real-time feedback. Especially, the applications based on tablet systems grow exponentially with the advantages of providing convenient learning and training environments [17]. As far as we know, few technology-assisted systems are available for hand preference assessment and hand skill training of children with ASD [18, 19]. In this context, we focus on developing a tablet game system that can motivate children with ASD to perform tasks requiring hand manipulations as well as record objective performance measures for hand preference and hand skill evaluation.

In this chapter, we propose a tablet game system on the Android platform that aims to assess the hand usage of children with ASD in collaborative games. Here the term “collaborative” refers to cooperation between two hands as well as between two players. To play these games, the players should coordinate the manipulations of two hands (of one/two players) to hit or avoid contacting the moving bubbles in the game space, which requires precise and quick hand movement manipulations, eye-hand coordination skill as well as interaction skills to communicate and cooperate with the partners. The system is capable of collecting objective and quantitative performance data of the players, which are used to analyze the hand usage of the players in the games. We expect that this system would provide an effective and efficient method to evaluate the hand usage and hand preference of children with ASD, and eventually enhance the hand skills and interaction skills among the children with ASD through the collaborative hand-control games.

The rest of this chapter is organized as follows. Section 3.3 introduces the design and implementation of the system. Section 3.4 describes the modes of playing the games in this system. Section 3.5 presents a small usability study. Section 3.6 discusses the study results followed by the summary of contributions and future work in Section 3.7.

3.3 System Design

The tablet game system was developed using Unity 3D [20]. The core of the system is the *Bubble Game* as shown in Figure 3-1. In the game, a number of blue bubbles and/or pink bubbles randomly move in the game space. The players are required to manipulate the collaborative tool by placing fingers on the touch plates to make the pin (the red point) of the tool hit the blue bubbles and simultaneously avoid contacting the pink bubbles, in order to achieve higher scores within a given time. Since the type, number, movement speed and direction of the bubbles in the game space could vary, the players should schedule their manipulations in an optimal order and adjust these manipulations flexibly. For example, when two blue bubbles move across the game space in different speeds, the player(s) should decide which bubble to hit first considering the distance of each bubble from the cross point, the distance of each bubble from the border and the manipulation efficiency.

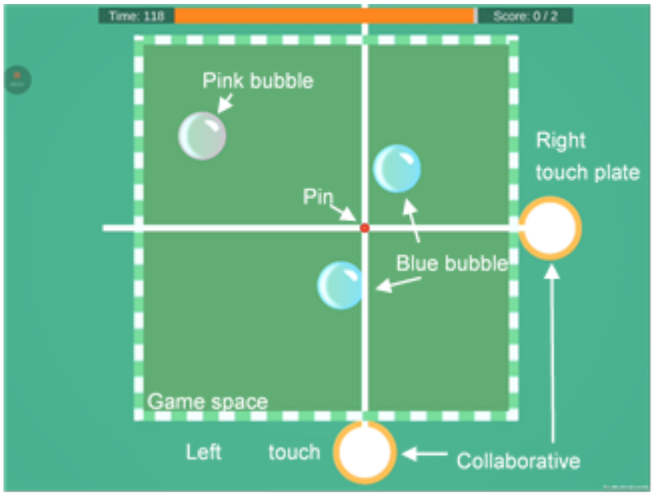

Figure 3-1. The *Bubble Game* interface.

The *Bubble Game* was implemented with five major modules as represented by the block diagram in Figure 3-2. The Main Controller addresses the communication and synchronization of all the components that comprise this game. In the following sections, we will describe the other five modules in detail.

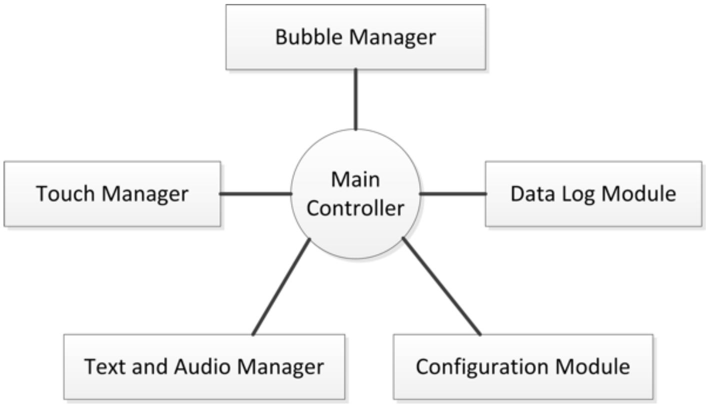

Figure 3-2. The *Bubble Game* architecture.

3.3.1 Bubble Manager

The Bubble Manager controls the behaviors of the bubbles by adjusting a number of bubble parameters. The parameters for one bubble are listed below:

- Color (c): it can be blue or pink. The blue bubble is a rewarding bubble that can improve the score when being hit, while hitting the pink bubble will reduce the score;

- Speed (v): a bubble's movement speed is randomly assigned from a specified speed range (v_{min}, v_{max});

- Start Point (x_0, y_0): it is the location from which the bubble moves into the game space. Thus, the start point will be near the borders of the game space (11.74 × 11.74). With the origin of the coordinate frame at the center of the game space, the values for the coordinate (x_0, y_0) of the start point are randomly chosen from $(\pm 6, range(-6, 6))$ or $(range(-6, 6), \pm 6)$. For example, if $(x_0, y_0) = (-6, 0)$, the bubble will enter the game space from the center of the left border;

- Destination Point (x_d, y_d): it is the location toward which the bubble moves. Destination point and start point together decide the motion trail of one bubble. For the blue bubbles, the destination points are located near the opposite border of the start point to make sure that the blue bubbles move across the game space and the players will have certain time to hit the blue bubbles. For instance, if the start point locates at $(x_0, y_0) = (-6,0)$, the coordinate of the destination point will be $(x_d, y_d) = (6, range(-6, 6))$ near the right border. For all the pink bubbles, there is only one destination point which is the location of the pin of the collaborative tool when the pink bubbles are spawned. The players thus need to be alert and protect the pin from the approaching pink bubbles.

Except for the above individual parameters, several group parameters are developed to make bubbles spawn in an orderly manner. These parameters are explained as follows:

- Spawn period (t_s): it is the period for spawning a wave of bubbles;

- Spawn interval (t_i): it is the interval between spawning a bubble in a wave;

- Blue number (N_b): it is the number of blue bubbles in a spawn wave;

- Pink number (N_p): it is the number of pink bubbles in a spawn wave. So the total number of the bubbles in a spawn wave will be $(N_b + N_p)$;

The Bubble Manager also performs the interaction logic of the bubble with the pin of the collaborative tool. When the pin touches one bubble, the bubble will burst and disappear from the game space. Accordingly, the player's score will increase (hitting the blue bubble) or decrease (hitting the pink bubble) by one.

3.3.2 Touch Manager

The Touch Manger obtains the input data in terms of finger location on the tablet screen and uses the data to control the collaborative tool. The collaborative tool consists of two touch plates (left touch plate and right touch plate), each of which is allowed to move along one direction within the game space (horizontal direction: $x \in (-5.72, 5.72)$ or vertical direction: $y \in (-5.72, 5.72)$). Once the location of the finger touching the screen falls within the area of one touch plate, the touch plate will move following the finger movement in horizontal or vertical direction. For instance, when one finger touches the left touch plate, the horizontal location of the left touch plate will be same as that of the finger, while its vertical location will not change.

3.3.3 Text and Audio Manager

To make the game more lively and understandable, we added some simple visual and auditory feedback. For instance, when one blue bubble is touched, a "+1" text is displayed in the game space and a bubble-burst audio is played to tell the players that they have scored a point. Similarly, when one pink bubble is contacted, a "-1" text is displayed. However, a different bubble-burst audio is played to warn the players that they touched the dangerous pink bubbles.

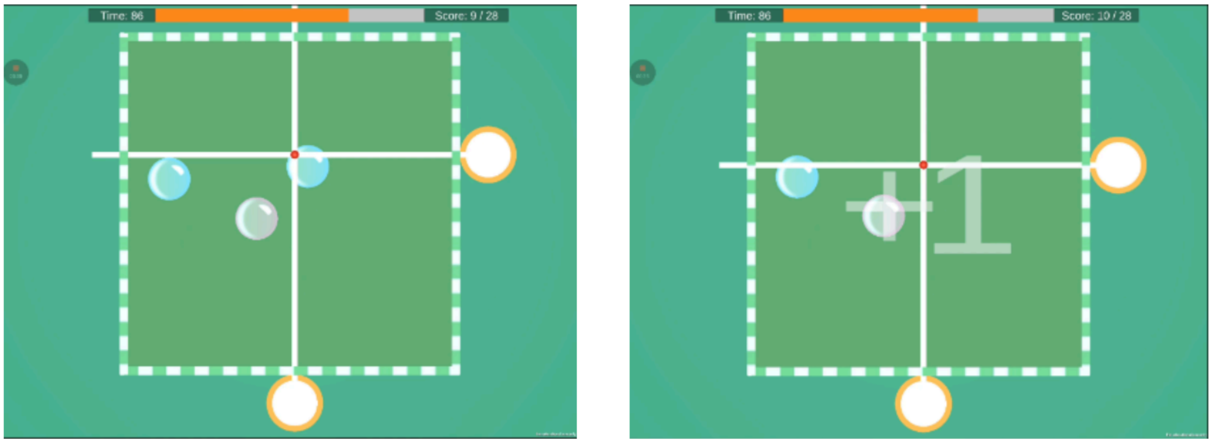

Figure 3-3. An example of the visual feedback. The "+1" text would display (in the right picture) when one blue bubble (the blue bubble near the pin in the left picture) is hit.

3.3.4 Configuration Module

The Configuration Module specifies the game settings, such as the bubble parameters mentioned in section 2.1. The data about the game settings and codes for game configuration update are saved and executed in this module. By adjusting the bubble parameters in this module, we developed and used three types of Bubble Games in the usability study: (1) *Blue Bubble Game*: only blue bubbles exist in the game space and the players are expected to hit all the blue bubbles; (2) *Pink Bubble Game*: only pink bubbles exist in the game space and the players are expected to avoid contacting all the pink bubbles; (3) *Blue-Pink Bubble Game*: both blue and pink bubbles exist in the game space. Every game lasts 2 minutes. Table 3-1 shows the detailed information about the game configurations for these three games.

Table 3-1. Game Configurations.

Games	N_b	N_p	$t_s(s)$	$t_i(s)$	(v_{min}, v_{max})
Blue Bubble Game	3	0	2.4	0.2	(2,6)
Pink Bubble Game	0	3	2.4	0.2	(4,6)
Blue-Pink Bubble Game	2	1	2.4	0.2	(2,6)

3.3.5 Data Logging Module

The Data Logging Module records game-related data and generates performance measures for offline analysis. These measures include:

- Score(S): it is computed as (the number of touched blue bubbles + the number of avoided pink bubbles) / (the total number of produced blue bubbles + the total number of produced pink bubbles) in one game. For example, we assume that in one *Blue Bubble Game* 98 blue bubbles and 49 pink bubbles were produced. The player successfully hit 80 blue bubbles and avoided touching 40 pink bubbles (touching nine pink bubbles). The final score for this player would be (80 + 40)/(98 + 49) = 0.81;

- Distances per motion (d_l, d_r): it is computed as (the sum of the displacements of left/right touch plate)/(the movement times of the left/right touch plate) in one game. For instance, we assume that a player moved the left touch plate 34 times with the total movement displacements equaling 366.74. Then the average left distance per motion was d l = 366.74/34 = 10.79. The average distances per motion reflect how many efforts the player spends during each motion manipulation.

3.4 Play Modes

Every *Bubble Game* can be played by one player or two players. For one player, he/she should use two hands, each of which controls one touch plate of the collaborative tool. Due to the influence of the handedness, we hypothesize that movement manipulations would be easier to perform using the dominant hand rather than the non-dominant hand. The players would spend more time and greater efforts to complete non-dominant hand manipulations though two hands are supposed to undertake equal work. For two players, each player is allowed to control one touch plate using either the dominant hand or the non-dominant hand. In this mode, the players' performances are affected by the usage of hand as well as the communicative and collaborative skills.

3.5 Usability Study

3.5.1 Participants

We recruited four children with ASD and four TD children for this study. All the participants were right-handed. They were divided into 4 ASD-TD pairs as shown in Table 3-2. The study was approved by the Vanderbilt University Institutional Review Board. Both sets of experiments were conducted after obtaining the assent of the participants, consents from their parents and under the supervision of trained ASD therapists and experimenters.

Table 3-2. Participant Characteristics.

Pair	**Gender**		**Age (years)**		**IQ**	**ADOS raw score**	**ADOS severity score**	**SRS-2 raw score**		**SRS-2 T-score**	
	ASD	**TD**	**ASD**	**TD**	**ASD**	**ASD**	**ASD**	**ASD**	**TD**	**ASD**	**TD**
1	F	F	9.97	10.26	114	13	8	66	2	66	39
2	F	M	7.81	10.26	101	17	9	106	3	82	38
3	F	F	9.07	7.56	/	/	/	89	2	75	38
4	M	F	10.19	9.77	101	10	6	81	29	69	50

3.5.2 Experimental Procedure

The main procedure for one single experiment with one pair of participants is showed in Figure 3-4. First, the paired participants separately played the three types of *Bubble Game* alone in different experimental rooms. As mentioned before, each of them used two hands to play these games. Next, two participants came to the same room and played the *Blue-Pink Bubble Game* together on one tablet. They were required to use their dominant hands first and then use their non-dominant hands to play the same game. At the end of the experiment, participants completed a survey with two questions to express their feedback regarding the experience of using this system.

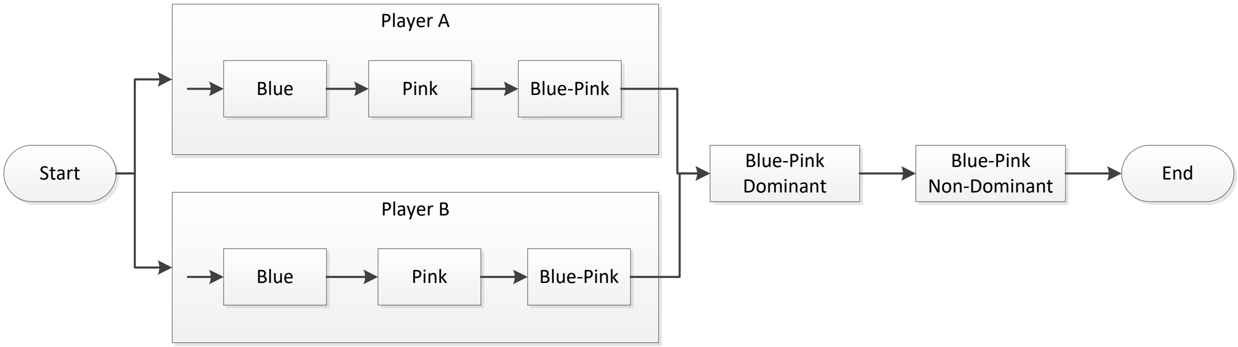

Figure 3-4. The experimental procedure.

3.6 Results and Discussions

All the participants completed the entire experiment. They could understand the game rules quickly and figure out how to play the games easily with a small amount of practice. Participants' answers to the survey showed that most of the participants (6 out of 8) liked the games "very much", while the other two participants (one participant with ASD and one TD participant) liked the games "a little". From our observation, the participants were engaged in the games and seemed to enjoy the entire experiment. In addition, all the participants preferred to play with a partner, except for one child with ASD who preferred to play by himself. From the game video records, we found that all the paired participants would talk with their partners spontaneously even though they did not know each other before. And they talked more when they played the second two-player game.

The performance results are showed in Figure 3-5. First, we can see that on the average participants played better in *Pink Bubble Games* than in *Blue Bubble Games*. It is reasonable since it is easier to avoid touching bubbles than to hit bubbles. When the games became more difficult and complex in *Blue-Pink Bubble Games*, both the average scores of participants with ASD and TD participants decreased a little bit. However, when they played the same games in the two-player mode, their scores increased a little bit even in the game requiring to use non-dominant hand. It might indicate that it was easier for participants to perform one-hand manipulations. And good communication and cooperation might also contribute to the increased scores.

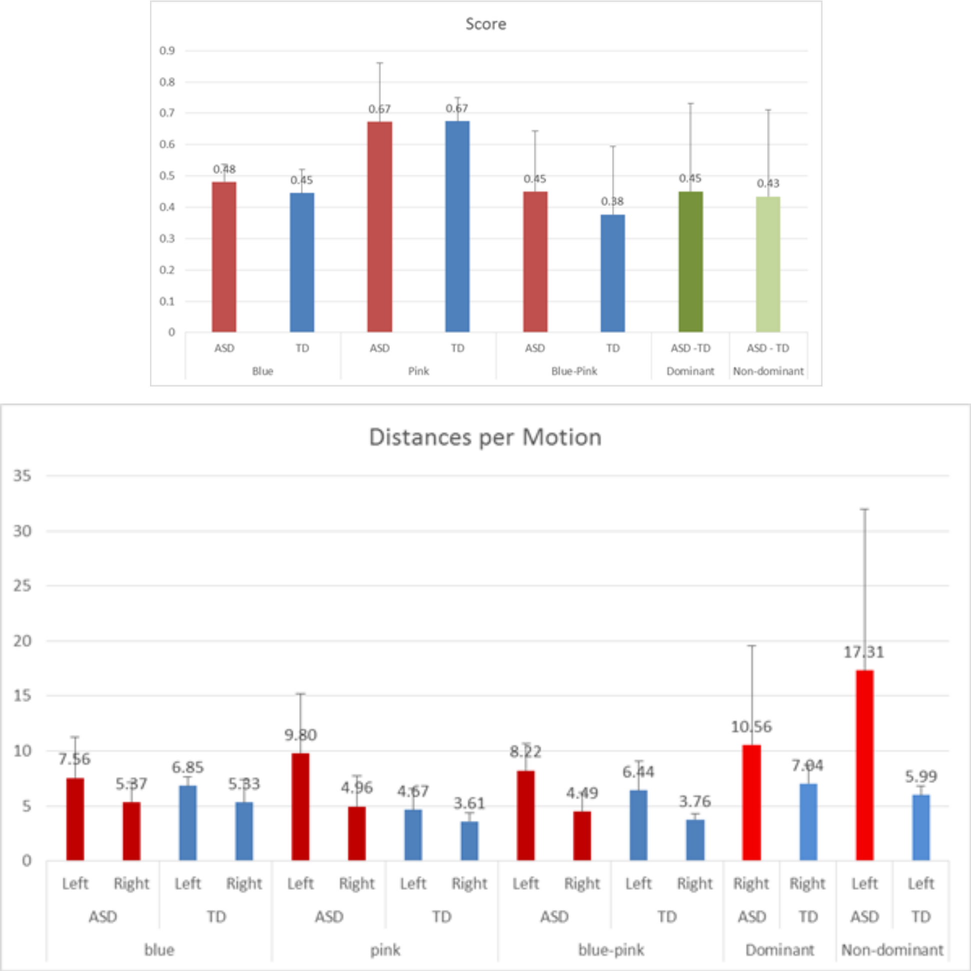

Figure 3-5. Performance results of participants. The top graph shows the average scores and the bottom graph shows the average distances per motion of each hand in different games.

Second, participants spent great efforts to perform non-dominant hand (left hand) manipulations in the one-player mode. The Wilcoxon Signed-ranks Tests indicated that the distances per motion of non-dominant hand for participants with ASD (mean = 8.527, median = 9.021) were significantly greater than those of dominant hand (mean = 4.937. median = 4.014), W = 78, Z= 3.059, $p < .001$, $r = 0.624$. The difference regarding the distances per motion between non-dominant hand (mean = 5.985, median = 6.176) and dominant hand (mean = 4.232, median = 3.7) for TD participants was also significant, W = 69, Z = 2.353, $p = .019$, $r = 0.480$. In addition, no significant difference was found between the distances per motion of non-dominant hand for participants with ASD and for TD participants (W = 61, Z = 1.726, $p = .084$, $r = 0.352$), as well as regarding the dominant hand (W = 53, Z = 1.098, $p = .272$, $r = 0.224$).

By computing the Pearson correlation coefficients, we found that the non-dominant hand and dominant hand of participants with ASD had strong positive relationship (r (10) = .716), while the relationship for TD participants was weak and positive (r (10) = .201). It indicated that participants with ASD tended to increase the intensity of one hand's manipulations as the other hand's manipulations increased. However, both hands' manipulations of TD participants were relatively independent. It might demonstrate that participants with ASD performed redundant or inefficient manipulations during playing the games. This assumption could be supported by the results of two-player games. We could see that the average distances per motion of non-dominant hand and dominant hand for participants with ASD were twice as many as those of one-player games though the achieved scores of two-player games increased just a little bit. And TD participants still remained at a similar level of the distances per motion in the two-player games.

3.7 Conclusion and Future Work

In this chapter, we have presented a tablet game system which is able to efficiently assess the hand usage of users in movement manipulations and to spontaneously induce communicative and interactive activities between the users via hand-control games. The preliminary usability study showed that the proposed system was attractive for participants with ASD and their TD peers. The participants also tended to play with their partners and communicated in a natural way when they played the games together. The performance results based on the logged data reflected the hand usage behaviors of the participants. From the results, we found that participants performed a little better in two-player games only requiring one-hand manipulations than in the one-player games requiring two-hand manipulations. Participants also took greater efforts to perform non-dominant hand manipulations in the one-player games. In addition, participants with ASD showed a strong and positive relationship between their two hands, while the relationship of both hands was weak among TD participants. The study results were limited but promising, which suggested the potential of this proposed system for assessing the hand usage and promoting collaborative hand manipulations of children with ASD. In the future, we will expand the sample size of the user study to further test the effectiveness of this proposed system as well as to investigate the relationship between the performance, hand manipulation and interactive skills.

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CHAPTER 4

A HAPTIC-GRIPPER VIRTUAL REALITY SYSTEM (HG) FOR ANALYZING FINE MOTOR BEHAVIORS IN CHILDREN WITH ASD

4.1 Abstract

Fine motor skills, including grasping, manipulating and reaching for objects, are a documented weakness for many children with Autism Spectrum Disorder (ASD). However, relatively less research has attempted to address these motor deficits, especially by taking advantage of advanced technology. To explore potential mechanisms for expanding accessibility to fine motor intervention for people with ASD, we present the design and implementation of a usability study of a novel Haptic-Gripper Virtual Reality System (Hg). Hg is capable of providing analysis and practice opportunities of fine motor skills in an adaptive and low-cost virtual environment with real-time auditory, visual and haptic feedback. The Haptic Gripper in Hg can detect a user's grip force and hand location, and provide haptic feedback to guide hand movement and grip control while completing several simple and engaging virtual fine motor tasks. We conducted a usability study with six children with ASD and six typically developing (TD) children, and found participants were interested in using the Haptic Gripper and could quickly get used to the system. Although the results are preliminary and limited, we observed medium to strong correlations between the proposed fine motor skill metrics and the scores achieved with a standardized fine motor skill test, and improvements of participants in accuracy and steadiness of movement and force control. In addition, features extracted from the performance data were used to recognize the motor patterns of children with ASD using machine learning approaches, which were found to be useful for distinguishing participants with ASD from TD participants with the accuracy up to 80%. These findings lend support to the promising potential of our system for fine motor skill analysis and training for individuals on the autism spectrum, which might expand the accessibility of efficient fine motor interventions.

4.2 Introduction

When referring to Autism spectrum disorder (ASD), people always focus on the core deficits of ASD in social communication and interaction [1]. However, the high prevalence of motor impairments and delays among ASD population cannot be overlooked [2]. Previous studies have noted several motor abnormalities of children with ASD, including atypical gait, postural control and upper limb movements [3-5]. In particular, atypical fine motor control, such as the abnormalities in eye hand coordination, grasping and reaching, and less accurate manual dexterity, is found among children with ASD [6-8].

Fine motor skills that coordinate the use of the fingers and hand with visual perception are commonly used in activities of daily life that require precision and steadiness, such as handwriting and tool manipulation [9]. Fine motor skills start developing in infancy (e.g. infant's reaching and grasping of objects) and are refined over time [10]. Previous studies have documented atypical fine motor control among children with ASD, such as abnormalities in grasping and reaching [6], eye-hand coordination [11], and handwriting skills [12]. These children might have poor motor planning and control, take a longer time to respond to valid cues or initialize a movement, exhibit increased movement duration and excessive associated movements, and find it difficult to negotiate complex movement [13-16]. Studies have shown that children's fine motor skills may be an indicator of later achievements [17, 18], and fine motor impairments might negatively affect children with ASD in physical, scholastic and social activities [19-21]. Therefore, it is necessary to investigate the fine motor ability of the children with ASD and provide accessible fine motor intervention for them. In addition, understanding and exploring the motor signatures in children with ASD might provide a new methodology to facilitate ASD diagnosis [22].

In this chapter, we present a novel Haptic-Gripper virtual reality system (Hg) for virtual fine motor skill training and analysis in a more engaging, objective and quantitative way. Hg consists of a customized haptic interactive tool, called Haptic Gripper (Figure 4-1), which was instrumented with force sensors. This customized tool can detect the user's hand location as well as the grip force, and provide real-time haptic feedback according to the user's fine motor manipulations. The virtual tasks designed for this system require users to grip virtual objects with appropriate grip force and move them steadily through specific paths toward targets, with the purpose of strengthening precision gripping skills as well as the ability to generate steady motion. The system is capable of automatically recording objective and quantitative data regarding the user's performance in order to analyze the user's finger and hand motor control abilities as well as to investigate whether fine motor information is useful to identify children with ASD.

The primary contributions of the current research are three-fold. First, we present the design and implementation of a novel haptic-gripper virtual system for analyzing and potentially improving the fine motor coordination skills of children with ASD. Second, we conducted a preliminary usability study to observe the acceptability of Hg in the target population, and to quantify the fine motor coordination skills using force and motion based metrics and tasks that require coordination of both hand and finger movement. To evaluate whether the proposed objective and quantitative metrics can be useful for the fine motor skill assessment, we investigated the correlation between the proposed metrics with the scores achieved through the Motor Coordination subtest of the Beery-Buktenica Developmental Test of Visual-Motor Integration (VMI Motor Coordination Test) [23], which is a commonly used instrument to assess an individual's fine motor skills. To explore the potential of Hg as a training system for improving the fine motor skill, we also compared the performance change of participants before and after one session of training using Hg. In addition, we investigated whether fine motor performance data are useful to identify children with ASD using machine learning approaches, and also investigated the most discriminant fine motor features that distinguish the children with ASD from their TD peers. We expected that properly trained classification models based on fine motor patterns could be a practical predictor for the future ASD diagnosis.

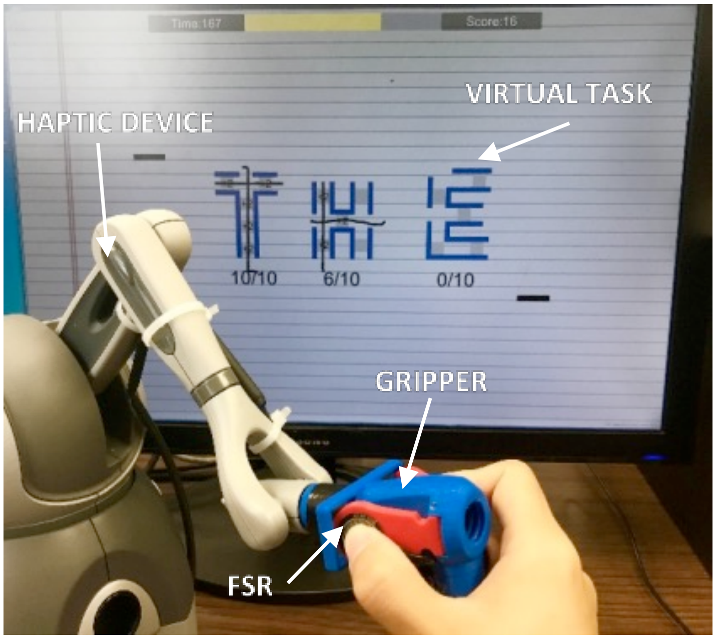

Figure 4-1. The use of the Haptic-Gripper virtual reality system (Hg).

The rest of the chapter is organized as follows. Section 4.3 discusses the related work on the investigation of fine motor ability of children with ASD. Section 4.4 presents the system design, which is followed by the usability study in Section 4.5. The results and discussions of the study are presented in Section 4.6. Finally, we summarize the contributions of the work and discuss its limitations in Section 4.7.

4.3 Related Work

In this section, we provide several prior works that explored the fine motor skills and fine motor patterns of children with ASD.

4.3.1 Related Work on Investigating Fine Motor Skills of Children with ASD

Given limited ASD intervention resources in the healthcare system [24] and with the documented affinity of many children with ASD for technology [25], a number of computer-assisted systems have been developed in recent years that provide an attractive, replicable, low-cost, quantitatively measurable, and controlled intervention environment with real-time feedback [26-29]. Fine motor tasks require a longer duration of attention and physical effort. Fine motor tasks in the form of computer games can deliver consistent and real-time rewards or consequences for responses, which can encourage engagement and retain children's attention [30]. For example, the haptic assisted handwriting training system developed by Kim et al. [31] provided a reward and punishment system, including a score relating to the user's performance, to encourage the user to explore increasingly challenging tasks. Haptic devices are capable of providing human-computer interactions through body contact and responding to human behaviors with mechanical force feedback. Several studies have reported that haptic devices are beneficial in increasing immersion and quality of task performance and thus enhancing training achievements [32-37]. For example, Khurshid et al. [32] examined the effects of grip-force, contact and acceleration feedback on a teleoperated pick-and-place task with a haptic device worn on the participant's hand. They found that grip-force and high-frequency acceleration feedback had positive effects on task performance. Sutherland et al. [33] proposed a haptic simulation system for spinal needle insertion training, and demonstrated that the system had the potential for reducing the need for the presence of live patients or cadavers or trained clinician. Morris et al. [34] explored the use of haptic feedback for improving the learning accuracy of force recall, and demonstrated that the combined visuohaptic training was more effective than either visual or haptic training alone. Gupta et al. [35] made a haptic arm exoskeleton for providing safe and repeatable rehabilitation and training in virtual environments. Patton et al. [36] showed the potential of haptic training in helping to restore reaching ability of patients with post-stroke hemiparesis. Patomäki et al. [37] designed a series of multimodal applications with haptic interface for visually impaired children to learn and play.

Research in computer-based systems to investigate the fine motor ability of children with ASD are diverse with respect to the targeted deficits, the instruments involved, and the measures and analysis used. A common way of assessing children's fine motor skills is through handwriting analysis [31, 38-42]. For example, Rosenblum et al. [38] indicated the unique handwriting characteristics of children with high-functioning autism spectrum disorder (HFASD) (age: 9-12) by using a computerized instrumentation consisting of a tablet, where the user performed writing tasks. They suggested that identifying ASD-specific handwriting features could provide a more comprehensive picture of individual deficits, and may contribute to more focused and adaptive intervention. Palsbo et al. [39] provided repetitive fine motor training of hand using a Falcon haptic device for children with fine motor deficits including children with ASD (age: 5-11), aiming to improve their handwriting legibility and speed. The haptic device was programmed to generate a 3D pathway when the user typed in letters, numbers or punctuation glyphs. They reported that this kind of hand training helped improve handwriting fluidity of children with ASD. Kim et al. [31] also developed a haptic assisted training (HAT) system for transferring and improving handwriting skill. The HAT system guided the user's hand along a sequence of strokes and provided the training tasks in the form of 3D games. They implemented the systems with two different haptic devices, Phantom Omni and Novint Falcon, and tested the systems with children (age: 6-11) grouped by typical and special need. The system was found to be well received by the children, who showed improvements in tracing alphabets. Johnson et al. [40] investigated the underlying factors (specifically relating to motor control) of macrographia in children with ASD (age: 8-13) by asking them to write a series of cursive letters using a tablet and a stylus. They observed significant instability of fundamental handwriting movements and atypical biomechanical strategies that contributed to larger and less consistent handwriting in children with ASD. Palluel-Germain et al. [41] conducted a study to indicate that the visuo-haptic device may increase the fluency of handwriting production of cursive letters in kindergarten age children (age: 5). Pernalete et al. [42] explored the possibility of improving eye-hand coordination in children with limited motor skills using a haptic interface, which could provide force feedback as well as inertia and viscosity effects. They found improved motor accuracy in participants after the haptic therapy.

While the overall hand manipulation was considered in the above-mentioned studies, few have investigated the training of grip force and grip patterns for fine motor manipulations. However, the importance of grip force in fine motor manipulation and atypical grip control in children with ASD is well-documented [6, 43-46]. Wang et al. [43] examined the grip force control of children with ASD (age: 5-15) by asking children to press on opposing load cells with their thumb and index finger. They found some distinct grip patterns between the children with ASD and the TD children, such as increased force variability among the ASD group when trying to sustain a constant force level. David et al. [44] investigated the grip and load force adjustments in children with HFASD (age: 8-19) using a precision grip task that required the children to pick up a target from a starting position, and placed it to a target position. They observed greater grip force at movement onset and a more variable performance of the ASD group as compared to the TD group. Falk et al. [45] developed a computer-based handwriting assessment tool consisting of a custom-built pen with pressure sensors, which could achieve grip force measurement during writing. They used this tool to objectively quantify handwriting proficiency and detect handwriting difficulties in children, and found that grip force describing the grip strategy and dynamics could be a useful indicator of handwriting legibility. Abu-Dahab [46] examined motor and tactile-perceptual skills in individuals with high-functioning autism (IHFA) (age: 5-21), and found impaired grip strength, motor speed and coordination in IHFA. They suggested that the assessment and intervention of motor and tactile-perceptual skills should be performed early because these skills are essential to school performance.

It can be seen from the aforementioned literature survey that a large number of children with ASD have deficits in fine motor skills, in part due to difficulties with precise hand motion control and steady grip control. However, to our knowledge, there is no other existing system that provides opportunities for both

(1) quantitatively assessing fine motor deficits, and (2) practicing such skills using systematically designed tasks that require both hand motion and grip control in a virtual environment with haptic feedback. Considering the importance of haptic immersion as well as grip control in addressing fine motor impairment of children with ASD, we present a novel human-computer interaction system that combines a haptic device with a custom designed grip control system and integrates them with a virtual reality environment where fine motor tasks can be practiced with real-time force and audio-visual feedback. We develop this system, called Hg, in the hope of expanding accessibility of efficient motor interventions for children with ASD.

4.3.2 Related Work on Investigating Fine Motor Patterns of Children with ASD

ASD diagnosis is a difficult and complex task due to the wide range of symptoms involved. Currently, ASD diagnosis relies on the clinical evaluation of autism-specific behaviors via standardized interviews, observations and questionnaires, which is often time- and resource-consuming [47]. As a growing number of studies evidence the existence of atypical motor patterns in children with ASD, understanding and exploring the motor signatures in children with ASD provide a new methodology to facilitate ASD diagnosis [22]. Currently, computer-assisted systems have been increasingly applied in ASD intervention taking advantage of providing an engaging intervention environment as well as recording objective and quantitative performance data [27, 29, 48]. The equipment with specific sensors to detect and measure motor information is easily accessible in recent days. Instead of using paper materials for motor function assessment, such as Beery VMI [23] and Mullen Scales [49], motor tasks in the form of computer tasks/games are more likely to be accepted among children with ASD, and are able to provide computational measures enabling the exploration of motor patterns using pattern recognition approaches.

Studies have used a variety of motor tasks to explore the motor signature of children with ASD. For example, Anzulewicz et al. identified children with ASD employing machine learning analysis of movement data from a tablet gameplay, and achieved a maximum classification accuracy of 93% [50]. Wedyan et al. found good classification results between high risk infants and low risk infants for autism by using data from an upper-limb movement task [51]. Crippa et al. used the data from a reach-to-drop task to classify children with ASD aged 2-4 from TD children, and obtained a high classification accuracy up to 96.7% using Support Vector Machine (SVM) [52]. Johnson et al. examined the handwriting difficulties of children with ASD relating to motor control, and found children with ASD had larger stroke heights, instability of movements and faster movement speed as compared to TD controls [40]. Calhoun et al. [53] identified the gait patterns using kinematic analysis that were significantly different between children with ASD and TD controls. Among the existing studies, most of them used motion tracking equipment that put several markers on the subject's body to collect motor information, which may cause interference, obstruct natural movement and require complex operations. Only a few studies employ embedded sensors and integrated devices to support a more comfortable and natural intervention environment [45, 50]. In addition, there is less research on investigating the subtle fine motor patterns of children with ASD. However, the increased need for early ASD diagnosis and the growing evidence that limited fine motor skills in infants with ASD [7, 54] indicate the importance and significance in exploring the fine motor predictor of ASD. For example, the work of LeBarton et al. suggested that fine motor skills could predict expressive language skills in infant siblings of children with ASD [55]. Gernsbacher et al. demonstrated the associations among early oral- and manual-motor skills and later speech fluency [56].

4.4 Hg System Design

Hg aims to provide engaging virtual tasks for children with ASD to practice delicate finger and hand manipulations. These tasks require the user to manipulate virtual objects through various shaped paths by appropriately adjusting grip force and hand motion. The user interacts with these tasks via a customized Haptic Gripper, which can detect the user's grip force and hand location as well as provide haptic feedback. The haptic feedback combined with visual and auditory feedback provide real-time manipulation guidance for the user. Figure 4-2 shows the major modules as well as the details of the task model in the Hg system. The *Input manager* addresses the input data in the form of hand location and grip force, and uses the data to manipulate the virtual objects in the tasks. As the core of the Hg system, the *Task Manager* manages the task selection and task execution processes. It guarantees that tasks are loaded in a proper order and initialized with the proper task elements. It also synchronizes the execution of all the task modes. The *Data Manager* records the user data as well as the task data at a sampling rate of 50 Hz. These data include the movement position data, the grip force data and other data that reflect the user's manipulations (e.g., the data about when and where the user touches the wall/targets). All the data are time-synchronized and saved into .csv files for offline analysis of the user's performance.

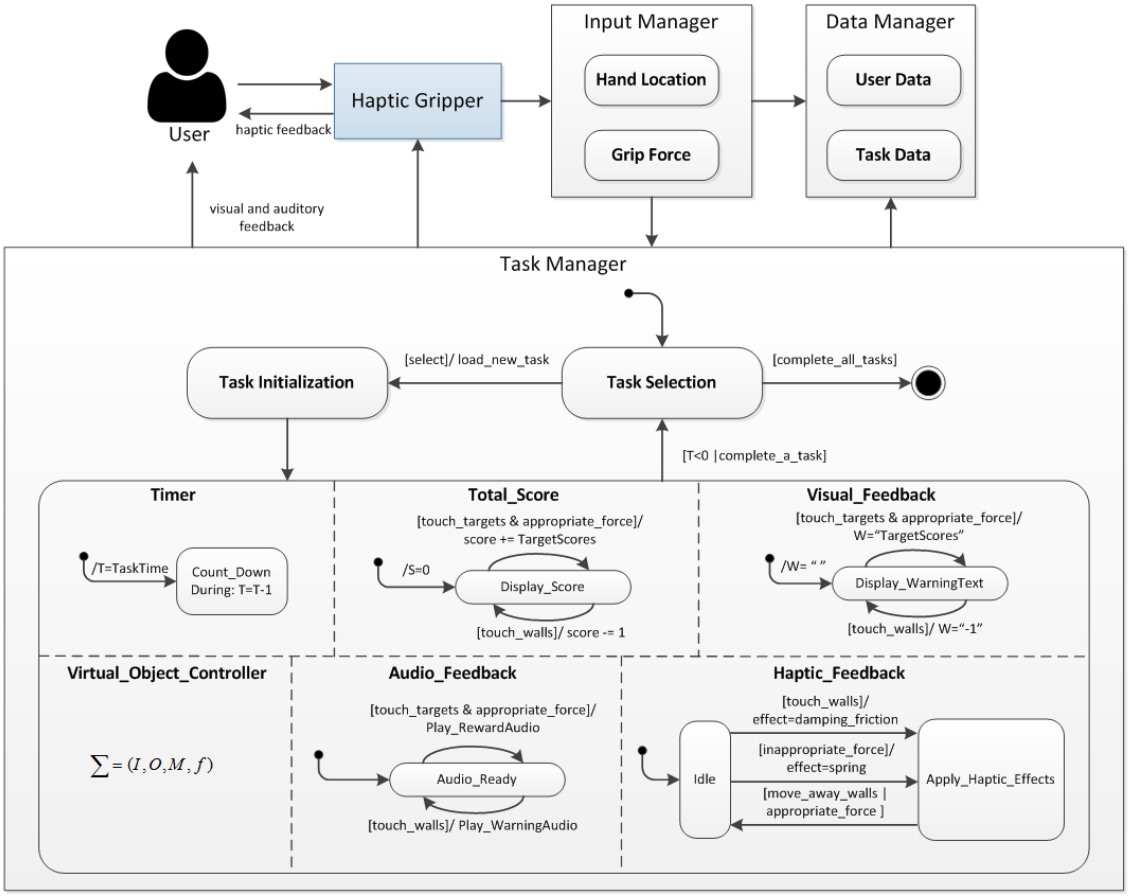

Figure 4-2. The system architecture with the major elements for implementing the system functionality. The Statechart diagram details the design of the Task Manager.

4.4.1 Haptic Gripper

The Haptic Gripper, as an interactive tool, was developed for the user to perform the task with one hand. As shown in Figure 4-1, it was constructed by augmenting a commercial haptic device, the Geomagic Touch Haptic Device [57], with a 3D-printed gripper embedded with force sensing resistors (FSRs). The Geomagic Touch Haptic Device was used in this system as the tool for manipulating the virtual objects as well as generating haptic responses in the form of friction, damping and spring force. This device allows operations in 6 degrees-of-freedom within the workspace (~6.4 W x 4.8 H x 2.8 D inch) and is able to provide an accurate measurement of 3D spatial position (nominal position resolution: 0.055mm). In addition, its motors can simulate stiffness and apply force feedback at 1 KHz rate, allowing the user to feel the virtual objects and providing true-to-life touch sensations. In this system, the Haptic Plug-In for Unity 3D [58] was utilized to implement the functionalities of the haptic device.

In order to integrate the grip manipulation, the stylus of Geomagic Touch Haptic Device was replaced with a 3D-printed gripper instrumented with FSRs as shown in Figure 4-1. The custom gripper was designed considering the hand features of the target users, who are 8-12 years of age [59] and was improved after our previous study with children with ASD [60]. The weight of the gripper is 35.55g. It consists of two press plates and a hollow handle. To use the gripper, the user holds the cylindrical handle and presses his/her thumb and index finger on the press plates that are connected to the gripper body by springs. According to the work of Schwellnus et al. [61], the mean grip force of Grade 4 children used in handwriting is 4.23N. Since many fine motor activities (e.g., drawing, turning a door key, etc.) require a low-level of forces similar to handwriting, the gripper was designed to provide low-level grip control requiring forces within the range 2.96N-5.50N by choosing appropriate springs.

Two FSRs from Interlink Electronics [62] are attached to the press plates to obtain grip force data. Both FSRs have 14.7mm diameter active area and have the force sensitivity range from 0.2N to 20N, which are suitable for our application. The FSRs communicate with an Arduino Uno microcontroller [63], which gets the FSRs data, performs data filtering and then transfers the data to the Input Manager at about 25 Hz. Before using the FSRs, we performed calibration by placing the FSR on a flat table and uniformly applying several known loads and obtained the relationship between the FSR data and the normal force.

4.4.2 Virtual Tasks

Children with ASD who have impaired fine motor skills will likely have poor manipulative skills. For example, they may exhibit grip force variability when drawing a straight line. They may apply inadequate grasp to use a tool. The virtual tasks designed in this system aim to evaluate and train user capabilities regarding grip control and grip adjustment during motion that call for cooperation of the eye, finger, hand and arm. Considering the young ages of target users, we created two tasks that were easy to understand for children with ASD. These tasks required users to move a virtual pen along a letter (*Letter Tasks*) or virtual balls along paths (*Path Tasks*) in order to reach targets, while avoiding hitting the wall.

All tasks were modeled using Statechart diagram and developed with Unity 3D [64]. As shown in Figure 4-2, six major modes are executed concurrently to implement the task logic. All tasks are time-limited. The *Timer* mode sets the total task time at the beginning of a task, records the remaining task time, and ends the task when the time is up. The *Score* mode updates the score when the user is touching the targets or walls and displays the score to the user. The *Virtual_Object_Controller* mode manages the behaviors of the controlled virtual objects using the model:

$$\sum = (I, O, M, f), \tag{4-1}$$

where $I = (H, G)$ represents a set of input data including hand location (H) and grip force (G), $O = (L,\ P)$

is a set of output data determining the location (L) and properties (P) of the virtual objects, M is a set of predicted output data that would become the final output data if they do not lead to improper behaviors (e.g. moving into the walls), and $f = (f_l, f_p)$ is a set of functions that are detailed later in the sections describing the tasks. The Visual_Feedback mode displays reward or warning texts to the user, while the Auditory_Feedback mode plays informative audios. The Haptic_Feedback mode determines the haptic effects the haptic device should simulate. This normalized model can be easily revised or expanded to design more force-driven or location-driven virtual tasks.

4.4.2.1 Task Controls

In this work, we focused on tasks that required both hand movement and grip control to strengthen skills in eye-hand coordination, movement stability, grip strength, movement and grip precision.

The goal of movement manipulation is to adjust the location of the virtual objects by moving the Haptic Gripper. The location and velocity of the Haptic Gripper is mapped to those of the controlled virtual objects. Note that the motion of the virtual objects is constrained to lie along a 2D plane, while the haptic gripper is allowed to move freely in the 3D workspace.

The grip manipulation in this system is in the form of two-fingered precision grasp with the thumb and the index finger [65]. It is designed based on the level of applied grip force and leads to different behaviors of the controlled objects in both *Path Tasks* and *Letter Tasks*. In the *Path Tasks*, the level of grip force would adjust the distance between the two virtual balls, while it would change the stroke thickness in the *Letter Tasks*. In this work, the grip force was divided into three ranges: (1) small (0-2.96N); (2) medium (2.96-5.5N); and (3) large (>5.5N). Forces belonging to different ranges would lead to different behaviors of the virtual objects as shown in Figure 4-3. In the presented usability study, we chose to use the medium grip force range as it covers the force range required for many fine motor manipulation tasks (e.g., handwriting).

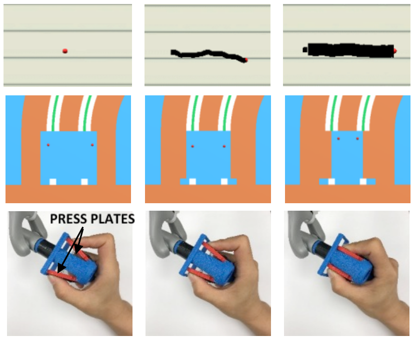

Figure 4-3. The behaviors of controlled stroke in *Letter Tasks* (the first row) and virtual balls in *Path Tasks* (the second row) as the user applies small (left), medium (middle) and large (right) grip force on the press plates of the Haptic Gripper.

4.4.2.2 Letter Task

Handwriting is an expected school activity that can be a challenging motor task for children with ASD [66]. The *Letter Tasks* simulated handwriting tasks by using the Haptic Gripper as the pen. In the *Letter Tasks*, the user only controls one ball, which is simulated as the tip of a virtual pen. Like drawing lines on paper, the user moves the virtual pen through several letter paths to obtain reward points (Figure 4-4). Based on the model (1), the location and stroke of the virtual pen is determined by:

$$
\begin{gathered}
L_{pred} = f_L(H) = V_0 + (H - R_0) \times scale_L \\
L = \begin{cases} L, & if \quad L_{pred} \in WallAreas \\ L_{pred}, & otherwise \end{cases} \\
P_{stroke} = f_P(G) = \begin{cases} P_{wide}, & if \quad F \in LargeRange \\ P_{narrow}, & if \quad F \in MediumRange \\ No\ rendering, & if \quad F \in SmallRange \end{cases}
\end{gathered}
\qquad (4\text{-}2)
$$

where L_{pred} is the predicted location of the virtual pen, computed by mapping the hand location data H with the mapping function f_L. V_0 and R_0 are the origin coordinate of the virtual world and the real world respectively. The virtual pen is forbidden to move into the walls. When the predicted locations of balls are inside the walls, the pen would stay at the last position in the free space. The grip force data change the stroke of the pen. When the user grips the press plates with a force beyond the small range, the motion trail of the ball is rendered. A medium grip force would produce a narrow rendered trail, while a large one would produce a wide trail. The user is expected to grip with medium force in order to obtain reward points in the letter path, and to move the ball steadily to avoid hitting the letter borders. We created three *Letter Tasks*, each of which includes one word from the sentence "THE LAZY DOG." The word "THE" contains straight lines, "LAZY" contains diagonals, and "DOG" contains curves. These three tasks thus provide practice opportunities in different kinds of strokes.

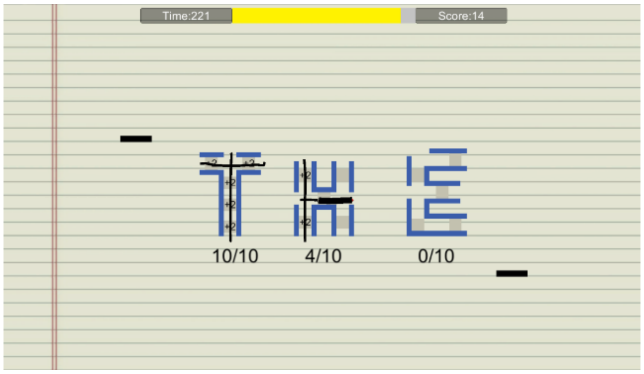

Figure 4-4. An example of the *Letter Task*, where the user is writing the word "THE".

4.4.2.3 Path Task

The Path Tasks require the user to control two balls, which are grouped together and move along various specified parallel paths. Two controlled balls were used instead of one in order to reflect the grip control through the relative position of the two balls, and to simultaneously raise the required level of eye-hand coordination. Based on the model (1), the locations of two balls are determined by:

$$L_{center\_pred} = f_L(H) = V_0 + (H - R_0) \times scale_P$$

$$P_{rel} = f_P(G) = \begin{cases} dis_{small}, & if \quad F \in LargeRange \\ dis_{medium}, & if \quad F \in MediumRange \\ dis_{large}, & if \quad F \in SmallRange \end{cases} \qquad (4\text{-}3)$$

$$L_{pred} = \begin{pmatrix} L_{pred}^{ball1} \\ L_{pred}^{ball2} \end{pmatrix} = \begin{pmatrix} L_{center\_pred} + P_{rel} \\ L_{center\_pred} - P_{rel} \end{pmatrix}$$

$$L = \begin{cases} L, & if \quad L_{pred} \in WallAreas \\ L_{pred}, & otherwise \end{cases}$$

The hand location data controls the location of the center of the grouped balls (L_{enter_pred}), while the grip force changes the relative distance between the center and the balls. When a small grip force is applied to the press plates, the relative distance remains at the maximum distance. As the grip force increases to the medium range, the two balls move closer to each other. And when the grip force reaches the large level, the distance becomes even shorter (Figure 4-3). Similar to the *Letter Task*, the virtual balls are only allowed to move within the allowable path areas.

Figure 4-5 shows a *Path Task*, in which the user moves the balls through the white curved paths to first touch the right targets and then bring them back to the left targets to get reward points. At first, the balls stay on the left side of the path entrance. The user has to adjust the distance of the grouped balls to fit the distance of the two paths in order to make sure both balls can pass through the paths. During the motion, the user should maintain a grip force within the medium range and be careful to prevent the balls from hitting the walls in order to receive a high score.

Eight *Path Tasks* differentiated by path shapes were designed. As shown in Figure 4-5, we created four straight and four curved paths in several orientations that comprise some of the basic strokes used to form a letter. In addition, we augmented these 8 tasks with path cues (green lines in Figure 4-5) to mark the routes where the balls are least likely to hit the wall, which could help reduce the risk of wall-hitting as well as determine which level of the grip force to apply.

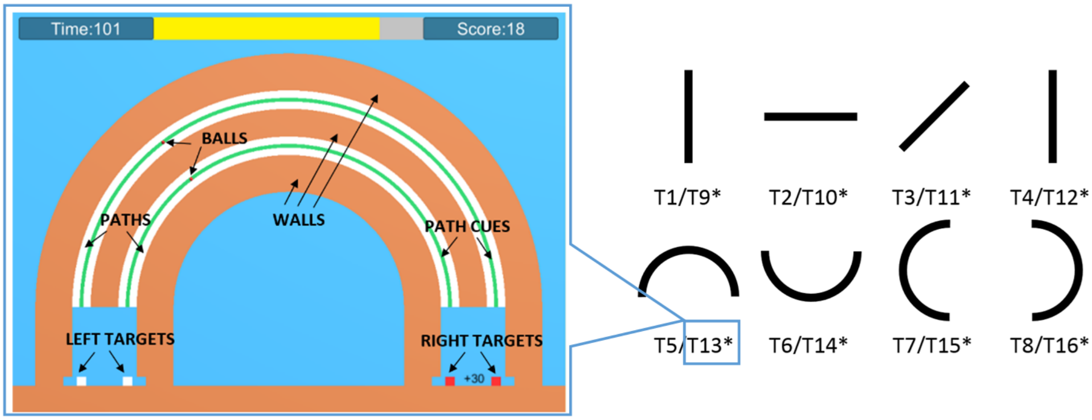

Figure 4-5. Examples of the *Path Task*.

4.4.3 Haptic, Visual and Auditory Guidance

Hg provides haptic, visual and auditory feedback to provide guidance when the user is performing some specific fine motor tasks.

The haptic feedback is a form of mechanical reaction felt by the user through the haptic device [65]. In Hg system, it is classified in three types: damping, friction and spring force. *We used the built-in methods of the OpenHaptics toolkit [67] with the Geomagic Touch Haptic Device to render all the haptic feedback.* First, when the controlled object make contact with the walls or targets which are simulated as hard surfaces, resistive force feedback is sent to the user to prevent the ball from penetrating the surface. The resistive wall force is computed based on a spring-damper model using the proxy-probe method:

$$F = -kx - c\dot{x}, \tag{4-4}$$

where k is the spring constant, c is the damper constant, and x is the displacement in the spring from the neutral position. As shown in Figure 4-6, the probe point is always at the position of predicted control point (probe position). In free space, the proxy point (the position of the controlled virtual object) is at the same position as the probe. But when the virtual object collides with the surface of another virtual object (e.g., wall), the proxy point is constrained to be on the surface of the other object and a simulated spring is stretched from the probe point to the proxy point to create simulated resistive force.

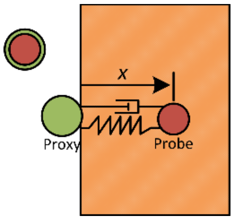

Figure 4-6. Proxy-probe method was used to realize the resistive feedback.

Second, static and dynamic friction forces are generated when the ball slides along the hard surface and they impede the lateral motion of the controlled object. These forces are computed using Coulomb's law of friction:

$$F = \mu N, \tag{4-5}$$

where μ is the coefficient of the static/dynamic friction and N is the normal force.

In addition, if the user applies improper grip force when moving the object through the paths, a spring force feedback is generated to prevent the object from moving forward. The spring force is calculated using the equation:

$$F = -kx, \tag{4-6}$$

where k is the spring constant and x is the displacement between the mapped control point and the anchor position that is the last position when the user applied the proper grip force. Because the Geomagic Touch Haptic Device can only render the force up to 3.3N, the above three kinds of feedback forces were limited in the range (0N, 3.3N). The parameters for rendering each haptic feedback were chosen within the range provided by the OpenHaptics toolkit [67] to guarantee stability.

The visual and auditory feedback occur with the haptic feedback to enhance manipulation guidance. For example, when the ball hits the wall, a warning text "-1" is displayed near the virtual ball and another warning text "Do not hit the wall!" is displayed on the screen. Simultaneously, a "crash" audio is sounded to inform that the collision happened and the score decreases by one point. When targets are touched, the targets become red, a reward audio is played and the reward points is displayed to encourage the user.

4.5 Usability Study

We conducted a usability study with six children with ASD (three males and three females) and six TD children (two males and four females). The goal of this study was to observe whether Hg could be well tolerated by the target population, and document the performances to analyze the impact of the system on the participants and the usefulness of the proposed performance metrics for assisting fine motor skill assessment and identifying the fine motor signatures of children with ASD. The study was approved by the Institutional Review Board of Vanderbilt University. Parental consent and participant assent were obtained prior to taking part in the study.

4.5.1 Participants

Twelve participants, six ASD and six TD who were 8-12 years of age, participated in this study. None of the participants had used any haptic device before, but they had played videogames and were able to complete handwriting tasks and simple drawing tasks independently. All participants were recruited through an existing clinical research registry. Table 4-1 shows the participant characteristics. The participants with ASD met the autism spectrum cutoff on the Autism Diagnostic Observation Schedule-Second Edition (ADOS-2) [68] The Stanford-Binet Intelligence Scales, Fifth edition (SB-5) [69] was employed to measure the intellectual functioning (IQ) of the participants, while the Social Responsiveness Scale, Second Edition (SRS-2) [70] was completed by participants' parents to index the ASD symptoms of their children. From the Table 4-1, we can see that the mean age and IQ were not significantly different.

Table 4-1. Participant Characteristics of TD Group (N = 6) and ASD group (N = 6)

Metrics	**TD Group M(SD)**	**ASD Group M(SD)**	***t (10)***	***p***
Age (years)	10.73(1.91)	9.66(1.36)	-1.12	.288
IQ	97.50(11.91)	106(7.1)	1.50	.164
SRS-2 total raw score	17.33(14.81)	82.67(26.32)	5.30	<.001
SRS-2 T score	44.5(6.53)	71.17(11.18)	5.05	<.001
SCQ Lifetime total score	3.67(2.16)	20.83(7.81)	5.19	<.001
ADOS-2 total score	/	17.4(2.30)	/	/

4.5.2 Procedure

The study procedure is illustrated by Figure 4-7. Each participant completed three major sessions in one day: a pre-test, an adaptive practice session, and a post-test. Each participant spent 40 minutes on average for this study.

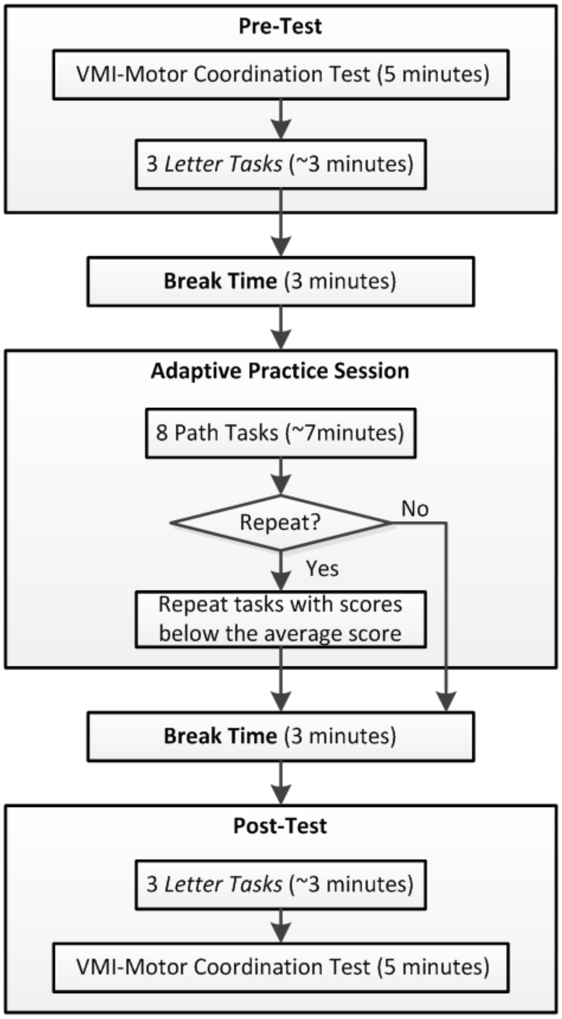

Figure 4-7. The experimental procedure.

The pre- and post-tests consisted of three Letter Tasks and a visual motor integration test to observe whether there were any differences in within system performance as well as in real-world tasks. To measure fine motor performance in real-world tasks, we used the Motor Coordination subtest of the Beery-Buktenica Developmental Test of Visual-Motor Integration (VMI Motor Coordination Test) [23]. The Letter Tasks assessed the within system fine motor skills of the participants that were practiced in the Path Tasks of the adaptive practice session (discussed below), because each letter was composed of straight lines and/or curved lines.

In the adaptive practice session, each participant first completed eight Path Tasks (T1-T8) without path cues. The maximum score possible for completing a task without errors was 60 points where participants achieved 30 points for reaching the right targets and the other 30 points for reaching the left targets and lost one point every time they hit the wall. The system recorded the scores and computed the average score of these eight tasks to decide if the participant should attempt more tasks and if so, which kinds of tasks should be repeated. A pilot study with unimpaired adults yielded an average score of 54 points. Based on this score, which happens to be 90% of the maximum possible scores, it was decided that if a participant scored 54 or higher, the participant's performance was adequate and he or she did not need to practice additional tasks. In this instance, the participant was allowed to rest for 3 minutes. If a participant scored lower than 54 points, the system would automatically repeat the tasks one more time and provide path cues to augment the visual guidance for the participant. Thus the participant got more opportunities to practice and improve relevant fine motor skills.

Before starting the pre-test, the experimenter introduced the Haptic Gripper system, and explained how to perform the tasks. Then the participant was asked to adjust the placement of the Haptic Gripper and the height of the chair in order to have a comfortable operating posture. After that, she/he would play two practice tasks (one Path Task T9 and one Letter Task with word "FOX") to get familiarized with the use of the Haptic Gripper as well as the basic task rules. They were allowed to repeat practicing these tasks until they were comfortable using the system. During the whole experiment, the participant was allowed to have a short break after each task to relax the hand and to have a 3-minutes break before and after the practice session. At the end of the experiment, the participant filled out a short user survey with the help of experimenters, who explained each question to the participants and encouraged them to express their true feelings as such feedback will help make the system better.

4.6 Results and Discussions

4.6.1 Acceptability of the Hg System

All 12 participants completed the whole session in the study. No one expressed the need to quit the study even though they were informed that they could withdraw at any time without giving any reason. Most of the participants expressed great interest in the haptic gripper and said that they would like to play games with the device even though none of the participants ever used any kind of haptic device before. Also, note that every participant could independently perform the tasks after just a short introduction of the system. No one showed confusion or frustration during the tasks.

Participants' responses to the short user survey could reflect how the participants think of the system. The survey contained three simple questions as shown in Table 4-2. The answers to the first question (TD: Mean (SD) = 3.67 (0.52), ASD: Mean (SD) = 3.67 (1.37)) and to second question (TD: Mean (SD) = 4.33 (0.52), ASD: Mean (SD) = 3.83 (1.17)) indicated the positive feedback of the participants for the tasks. The answers to the third question suggested that haptic and visual feedback was the most useful type of feedback provided by the system.

Table 4-2. Survey Feedback of TD Group (N = 6) and ASD group (N = 6)

No.	Questions	TD Group Mean(SD)	ASD Group Mean(SD)
1	How much did you like playing these games? Choices: Very much (5), A little, Neutral, Not much, Not at all (1).	3.67(0.52)	3.67(1.37)
2	How easy was it to understand how to play these games? Choices: Very easy (5), Easy, Neutral, Difficult, Very difficult (1).	4.33(0.52)	3.83(1.17)
3	Which types of feedback were useful to help you play better in the games, haptic(H), visual (V) and/or audio (A) feedback? [a] Choices: Haptic feedback, Visual feedback, Audio feedback.	H (yes: 4), V (yes: 4), A (yes: 3)	H (yes: 5), V (yes: 5), A (yes: 3)

[a] One Participant in the TD group did not answer the third question.

Based on the experimenters' observations and the participant feedback, the participants did not face any difficulty in using the system and did not resist the use of haptic device. The Hg system and the associated tasks were acceptable to the study participants.

4.6.2 Analysis of Fine Motor Skills with Quantitative Metrics

Several performance metrics were derived from the recorded data to analyze the fine motor skills of participants (Table 4-3).

Table 4-3. Performance Metrics.

Metrics	Description
Grip Force Inside/Outside Path (F_{in}, F_{out})	The average values of the overall grip force the user applies inside the path or outside the path.
Grip Force Variation Inside/Outside Path (CV_{in}, CV_{out})	The coefficient of variations of grip forces that are calculated as the ratio of the standard deviation to the average of F_{in} and F_{out}.
Position Error (*PE*)	The root-mean-square error (RMSE) between the actual position of controlled virtual object and the optimal position in the letter path.
Movement Speed (*V*)	The average value of the overall movement speeds the user generates during the letter path.
Speed Variation (CV_v)	The coefficient of variation of the overall movement speeds that are computed as the ratio of the standard deviation to the average of *V*.
Task Score (TS)	The ratio of the final points (the difference between the total reward points and the total penalty points) to the maximum points.
Task Efficiency (TE)	The final points divided by the completion time in one task.

To assess grip control, we measured the average grip force (*F*) the participants applied during the task as well as the grip force variation (CV_F), which suggested the degree of variability in grip force. Because the *Letter Tasks* were designed to require medium grip force to write the letters inside the letter path and allow to apply grip force freely outside the letter path, the participant was anticipated to apply different grip forces when moving inside the letter path than when outside the letter path. Thus, we evaluated the grip control in different cases (F_{in}, F_{out}, CV_{in}, CV_{out}).

As for the hand movement control, we measured the position error (*PE*), movement speed (*V*) and speed variation (CV_v). The position error measured the position difference from the actual position to the optimal position in the letter path. Lower position error suggested that participants tended to move closer to the center of the paths and thus reduce the risk of hitting the walls. The movement speed indicated how fast the movement manipulation was performed, while the speed variation indicated the degree of variability in movement speed.

To evaluate the overall performance, we computed the task score (*TS*) and task efficiency (*TE*). During the tasks, the participants got reward points when completing a letter and lost points when hitting the wall. The final points the participant got for one task was the difference between the total reward points and the total penalty points. The task score was defined as the final points divided by the maximum points the task provided. The task efficiency considered the completion time the participant used for one task and indicated the achieved points per minute.

We used Spearman' rank correlation analysis to investigate the correlation between the proposed performance metrics and VMI Motor Coordination Test scores (VMI scores). Table 4-4 presents the correlations for all participants as well as for TD group and ASD group. The correlation directions were consistent in two groups. Significant correlations ($p < .05$) were only found between force-related data and VMI scores.

Table 4-4. Correlations between Performance Metrics and VMI Scores.

Metrics	**All**		**TD Group**		**ASD Group**	
	ρ	p	ρ	p	ρ	p
F_{in} (N)	0.488	.016*	0.618	.032*	0.352	.262
CV_{in}	-0.487	.016*	-0.523	.081	-0.430	.163
F_{out} (N)	0.427	.038*	0.414	.181	0.345	.272
CV_{out}	-0.442	.031*	-0.235	.462	-0.366	.242
PE(cm)	-0.301	.153	-0.358	.253	-0.310	.327
V(cm/s)	-0.148	.491	-0.239	.455	-0.232	.467
CV_v	0.017	.937	0.284	.371	0.063	.845
TS	0.276	.192	0.368	.239	0.332	.292

$*p<.05$

Since normality of this small sample (N = 6 for each group) could not be assumed, we used the Wilcoxon signed-rank test to compare participant pre- and post-test performance, and used the Wilcoxon rank-sum test to explore the group differences [71]. We report *r* effect sizes with the significance cutoffs of large (>0.5), medium(>0.3) and small (>0.1) [72]. Table 4-5 presents the means and standard deviations, the percentage of change from pre-test to post-test, and the test results.

Table 4-5. Performance Results of TD Group (N = 6) and ASD group (N = 6)

Metrics	**TD Group**						**ASD Group**					
	Pre	**Post**	***RC* *(%)***	***Z***	***p***	***r***	**Pre**	**Post**	***RC* *(%)***	***Z***	***p***	***r***
	Mean (SD)	**Mean (SD)**					**Mean (SD)**	**Mean (SD)**				
F_{in} *(N)*	3.63 (0.41)	3.69 (0.35)	1.65	-0.52	.600	-.15	3.34 (0.294)	3.84 (0.31)	15.0	-1.99	.046*	-.58
CV_{in}	0.31 (0.08)	0.25 (0.06)	-19.4	2.20	.028*	.64	0.35 (0.18)	0.26 (0.11)	-25.7	1.78	.075	.51
F_{out} *(N)*	1.78 (0.44)	2.01 (0.32)	12.9	-1.99	.046*	-.58	1.60 (0.66)	1.88 (0.43)	17.5	-1.15	.249	-.33
CV_{out}	0.89 (0.34)	0.67 (0.13)	-24.7	1.99	.046*	.58	0.98 (0.37)	0.83 (0.27)	-15.3	1.99	.046*	.58
PE(cm)	0.37 (0.04)	0.36 (0.05)	-2.7	0.52	.600	.15	0.39 (0.08)	0.37 (0.05)	-5.13	1.15	.249	.33
V(cm/s)	4.15 (1.17)	4.22 (0.50)	1.69	-0.31	.753	-.09	4.31 (1.31)	4.78 (0.96)	10.9	-1.78	.075	-.51
CV_v	1.48 (0.09)	1.48 (0.15)	0	-0.52	.600	-.15	1.62 (0.38)	1.39 (0.08)	-14.2	2.20	.028*	.64
TS	0.73 (0.13)	0.80 (0.11)	9.59	-0.94	.345	-.27	0.53 (0.73)	0.74 (0.29)	39.6	-0.94	.345	-.27
TE (/minute)	21.38 (3.96)	27.20 (5.54)	28.2	-1.99	.046*	-.58	17.54 (18.25)	27.74 (7.47)	58.2	-2.2	.028*	-.64
VMI	94 (4)	105 (6)	11.7	-2.21	.027*	-.64	89 (11)	102 (11)	14.6	-2.2	.028*	-.64

VMI, scores on the VMI Motor Coordination test

*RC, relative change computed by (post - pre)/pre *100%*

**p<.05*

4.6.2.1 Grip Control

As participants executed virtual pen strokes within the outlines of the letters, they were required to apply forces (F_{in}) within 2.96-5.50N in order to get reward points. The correlation analysis indicated that F_{in} was positively correlated to the VMI scores in both TD and ASD group. Significant correlation was found in

TD group ($\rho = 0.618$, $p = .032$), while medium correlation was found in ASD group ($\rho = 0.352$, $p = .262$). The correlations suggested increasing force within an allowable range might contribute to higher VMI scores. The performance analysis indicated that compared to the TD group who applied similar forces in both pre- and post-test (TD: $RC = 1.65\%$, $Z = -0.52$, $p = .600$, $r = -.15$), the ASD group significantly increased the applied force in post-test with a large effect size (ASD: $RC = 15\%$, $Z = -1.99$, $p = .046$, $r = -.58$). In the pre-test, the ASD group applied smaller forces than the TD group. Though no significant difference was detected, a medium effect size existed between the TD group and ASD in the pre-test ($Z = 1.20$, $p = .229$, $r = .35$). Force data suggested that in the pre-test, participants in the TD group were able to quickly find and steadily maintain proper forces, while most in the ASD group tended to apply small forces closer to the lower limit of valid force range. However, the ASD participants gradually increased the applied forces, and after the practice session, the ASD group applied much larger forces in the post-test. In addition, the Force Variation Inside Letter (CV_{in}) was negatively correlated to the VMI scores. Large correlation was found in TD group ($\rho = -0.523$, $p = .081$), while medium correlation was found in ASD group ($\rho = 0.430$, $p = .163$). The correlations suggested that lower variability in grip force might lead to higher VMI scores. The performance analysis found that CV_{in} significantly dropped in the TD group with a large effect size (TD: $RC = -19.4\%$, $Z = 2.20$, $p = .028$, $r = .64$), and also decreased in the ASD group with a large effect size (ASD: $RC = -25.7\%$, $Z = 1.78$, $p = .075$, $r = .51$). The results implied that both groups were able to maintain stable grip force while writing after practicing fine motor tasks in the practice session.

Outside the letters, participants were allowed to freely grip the Haptic Gripper. Results showed that both groups applied smaller grip forces ($F_{out} < 2.96$N) outside the letters, which indicated that there were significant differences in grip force between when one was writing (Fin) and when one was simply holding the gripper (F_{out}) (TD: $Z = 2.20$, $p = .028$, $r = .64$; ASD: $Z = 2.20$, $p = .028$, $r = .64$). Simultaneously, the Spearman's rank correlation analysis indicated large positive relationships between F_{in} and F_{out} (TD: $\rho = 0.714$, $p = .111$; ASD: $\rho = 0.543$, $p = .266$), which suggested the consistency of grip forces applied by the participants. As both groups increased Fin in the post-test, we also found that both groups increased F_{out} in the post-test (TD: $RC = 12.9\%$, $Z = -1.99$, $p = .046$, $r = -.58$; ASD: $RC = 17.5\%$, $Z = -1.15$, $p = .249$, $r = -.33$). In addition, the correlation analysis also suggested that smaller CV_{out} might help improve the VMI scores (All: $\rho = -0.442$, $p = .031$). Both groups achieved significant decreases in force variations outside the letter (CV_{out}) with large effect sizes (TD: $RC = -24.7\%$, $Z = 1.99$, $p = .046$, $r = .58$; ASD: $RC = -15.3\%$, $Z = 1.99$, $p = .046$, $r = .58$), which suggests that both groups reduced the force variability outside the letters. Though no requirements were set for how the user should grip when he/she was not writing, the grip strategy and variability seemed also important that could affect the performance.

4.6.2.2 Hand Movement Control

The correlation analysis indicated the medium negative relationships between the position errors (*PE*) and the VMI scores (TD: ρ = -0.358, *p* = .253; ASD: ρ = -0.310, *p* = .327). Significant negative relationships between the position errors (*PE*) and the virtual task scores (*TS*) were also found (TD: ρ = -0.832, *p* <.001; ASD: ρ = -0.883, *p* < .001). It was reasonable to expect that moving closer to the optimal path could achieve higher scores. Though no statistically significant differences were found in either the TD or ASD group regarding the position error (*PE*), both group decreased the average position errors in the post-test (TD: *RC* = -2.70%, *Z* = 0.52, *p* = .600, *r* = .15; ASD: *RC* = -5.13%, *Z* = 1.15, *p* = .249, *r* = .33).

The correlation analysis indicated that only small negative relationships were found between the movement speed (*V*) and the VMI scores (TD: ρ = -0.239, *p* = .455; ASD: ρ = -0.232, *p* = .467), and small positive relationships between the speed variation (CV_v) and the VMI scores (TD: ρ = 0.284, *p* = .371; ASD: ρ = 0.063, *p* = .845). These results suggested that the movement speed did not have much influence on the performance of the VMI Motor Coordination Test. However, significant negative relationships were found between the movement speed (*V*) and virtual task scores (*TS*) (TD: ρ = -0.601, *p* = .039; ASD: ρ = -0.592, *p* = .043), suggesting that the movement speed was an important factor affecting the task performance. The performance analysis showed that in either pre-test or post-test, the ASD group tended to move faster than the TD group on average. Especially in the post-test, while the TD group maintained the similar movement speed (*RC* = 1.69%, *Z* = -0.31, *p* = .753, *r* = -.09) and similar speed variations (*RC* = 0%, *Z* = -0.52, *p* = .600, *r* = -.15), the ASD group showed increase in movement speed (*RC* = 10.9%, *Z* = -1.78, *p* = .075, *r* = -.51) and significant decrease in speed variation (*RC* = -14.2%, *Z* = 2.20, *p* = .028, *r* = .64), which might suggest that the ASD group moved more smoothly in the post-test even when increasing the movement speed.

4.6.2.3 Performance Improvement

Scores on the VMI Motor Coordination test (*VMI*) indicated that participants in both TD group and ASD group achieved statistically significant improvements on the post-test, with large effect sizes (TD: *RC* = 11.7%, *Z* = -2.21, *p* = .027, *r* = -.64; ASD: *RC* = 14.6%, *Z* = -2.20, *p* = .028, *r* = -.64). According to the VMI standard score interpretation [23], the performance of the TD group remained at the average level (90-109) in both pre- and post-test, while the ASD group stayed at the below-average level (80-89) in the pre-test and reached the average level in the post-test.

Unlike the VMI Motor Coordination test that was completed within exactly 5 minutes, the virtual fine motor tasks were ended when the user achieve the task goals. Thus, except for the task score (*TS*), we also used the task efficiency (*TE*) that considered the time variable as the task performance metric. The performance analysis indicated significant improvements with large effect sizes (TD: *RC* = 28.2%, *Z* = -

1.99, p = .046, r = -.58; ASD: *RC* = 58.2%, Z = -2.20, p = .028, r = -.64) in both groups. Typically, the ASD group achieved significant improvements in all three tasks with large effect sizes ("THE" task: *RC* = 35.7%, Z = -2.20, p = .028, r = -.64; "LAZY" task: *RC* = 77.3%, Z = -2.20, p = .028, r = -.64; "DOG" task: *RC* = 56.3%, Z = -1.99, p = .046, r = -.58). The improved raw task scores *(TS)* also existed in both groups, but no statistically significant differences between pre- and post-test were found in either the TD or ASD group (TD: *RC* = 9.59%, Z = -0.94, p = .345, r = -.27; ASD: *RC* = 39.6%, Z = -0.94, p = .345, r = -.27).

The performance improvements in both *VMI* test and virtual test suggested that the virtual practice tasks (*Path Tasks*) had positive impact on improving the finger and hand motor control. Medium positive relationships between the virtual task scores (*TS*) and the VMI scores (TD: ρ = 0.368, p = .239; ASD: ρ = 0.332, p = .292) were found, which also suggested the effectiveness of the tasks in our system to evaluate the user's fine motor abilities.

4.6.3 Exploration of Fine Motor Patterns

We used the performance data from the eight *Path Tasks* in the adaptive practice session to explore the fine motor patterns of children with ASD.

4.6.3.1 Feature Extraction

We used four types of performance metrics, including:

- Task Duration: the time one participant took for completing one task.
- Hit Number: the times of the grouped balls hitting the walls.
- Grip Force: a set of force data one participant applied in one task.
- Location: a set of location data of the grouped balls in one task.

From the Location data, we derived the Speed metric that were a set of movement speed data of the grouped balls in one task. We also generated the Root-Mean-Square Error (RMSE) metric to indicate the motion stability, which measured the distance between the location of the ball and the center of the path. In addition, by dividing each task into two sub-processes: (1) go forward through the paths (GO process), and (2) go backward through the paths (BACK process), we derived sub-metrics for each sub-process. For instance, "D_GO" represented the duration of completing the "go forward" sub-process, while "D_BACK" for the "go backward" sub-process.

In this study, we only considered features of time domain that were frequently employed in the activity recognition literature [73, 74]. For each type of metric, we extracted several features. We also combined some features when appropriate. Table 4-6 includes the final chosen performance metrics and corresponding features extracted from these metrics. For Task Duration, Hit Number and RMSE, except for the original data, we extracted the "difference" feature, which was defined as the difference between the BACK process data and GO process data. As for the Grip Force and Speed, we extracted more features, such as the mean, median, standard deviation and so on.

Table 4-6. Performance Metrics and Features.

Types	**Metrics**	**Features**
Task Duration (D)	D, D_GO, D_BACK	Original metric, difference.
Hit Number (H)	H, H_GO, H_BACK	
RMSE (E)	E, E_GO, E_BACK	
Grip Force (F)	F, F_GO, F_BACK	Difference, mean, median, standard deviation, coefficient of variation (COV), interquartile range, skewness, kurtosis, mean/median absolute deviation (mad), maximum
Speed (V)	V, V_GO , V_BACK	

4.6.3.2 Feature Selection and Classification

The number of the overall extracted features was 59. We first ranked all features by F-values using one-way analysis of variance (ANOVA) test [75], and generated a feature list that arranged all features in descending order of F-values. Since some features were redundant to improve the accuracy of the classification model, we reduced the highly-related features (correlation > 0.9) to a single feature with a higher F-value, and finally obtained 35 features. To select the most discriminative features, we conducted the model training and evaluation on a subset of the feature list, where the subset size increased from 1 to 35. The feature subset was constructed by iteratively inserting a feature from the top of the feature list to the feature subset.

We trained six classifiers (Table 4-7) on our dataset (96 samples), and used the leave-one-out cross validation (LOOCV) for model evaluation. LOOCV is widely used when only a few data are available and is known to be almost unbiased [76]. LOOCV works by repeatedly selecting one sample from the dataset as the test set and using the remaining samples as the training set. In this study, the classification accuracy was evaluated using F_1 score, which considered the precision (*P*) and the recall (*R*) of the classification results. The F_1 score for each model was computed as:

$$F_1 = 2 \times \frac{P \times R}{P + R}, \quad (4\text{-}7)$$

$$P = \frac{TP}{TP + FP}, R = \frac{TP}{TP + FN} \quad (4\text{-}8)$$

where *TP* was the number of ASD samples that were correctly classified as the member of ASD group, *FP* was the number of TD samples that were incorrectly classified as the member of ASD group, and *FN* was the number of ASD samples that were incorrectly classified as the member of TD group. The whole procedure of model training and evaluation is described in Figure 4-8.

```
Procedure Model_Training&Evaluation(Data)
    Inputs
        Data: a dataset of N samples. Each Sample contains one
              label and FN features(in descending order of F-values)
    Output
        F1_scores: a set of F1_scores of models with 1-FN features
    for k := 1 to FN do
        Data_k <- Data with k features
        for i := 1 to N do
            test_set <- sample i of Data_k
            training_set <- remaining samples of Data_k
            build a model using training_set
            test the model using test_set and update TP, FP, FN
        compute F1_score for the model with k features
    return F1_scores
```

Figure 4-8. The procedure of model training and evaluation.

4.6.3.3 Classification Results

Figure 4-9 shows the classification results of six classifiers with respect to the number of features. Table 4-7 lists the maximum F_1 scores for each classifier. The results indicated that all classifiers could achieve maximum accuracies within 67-80% by considering appropriate features. The k-NN and ANN classifiers had the best performance with the maximum accuracy of 80%, when the k-NN classifier used the top one feature (Mean of Grip Force during the BACK process) and the ANN classifier used the top six features. The Naïve Bayes and the Random Forest classifiers had the second best performance with the maximum accuracy of 75%, when they separately used the top 5 and 11 features. The SVM and Decision Trees classifiers had lower accuracies of 71% and 67% respectively.

Table 4-7. Classification methods and results.

Classifiers	Parameters	# features	Max F_1
Decision Trees	CART algorithm	5	0.67
Random Forest	50 random trees	11	0.75
Naïve Bayes	Gaussian	5	0.75
k-Nearest Neighbor (k-NN)	k = 7, Euclidean distance	1	0.80
Artificial Neural Network (ANN)	1 hidden layer (4 neurons)	6	0.80
Support Vector Machine (SVM)	Radial basis function kernel	18	0.71

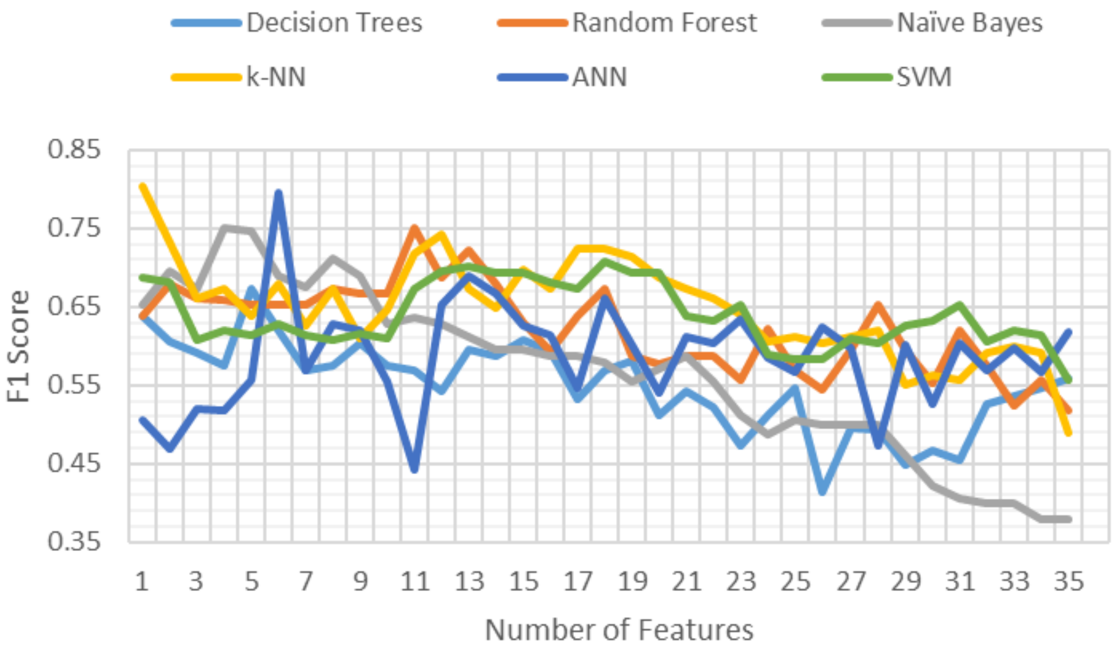

Figure 4-9. Classification Results.

According to the results of the ANOVA test, the top 10 features (all with p<.05) are related to the Grip Force (six features) and Speed data (four features). It suggested that Grip Force and Speed data provided much information for improving the classification of participants with ASD. The boxplots of the top 10 features (Figure 4-10) indicated that the ASD group applied significantly smaller Grip Force than the TD group (BACK_Fmean, Fmedian, GO_Fmedian). During the BACK process, the TD group increased much more Grip Force than the ASD group (DIFF_Fmean, DIFF_Fmedian), and reduced the variability of Grip Force much more than the ASD group (DIFF_Fmeanmad). In addition, during the GO process, the ASD group had greater Speed than the TD group (GO_Vmean), and had a lower kurtosis of Speed (GO_Vkurtosis). During the BACK process, the TD group reduced the COV of Speed much more than the ASD group (DIFF_Vcov). During the whole process, the ASD group had greater variability of Speed than the TD group (Vmeanmad).

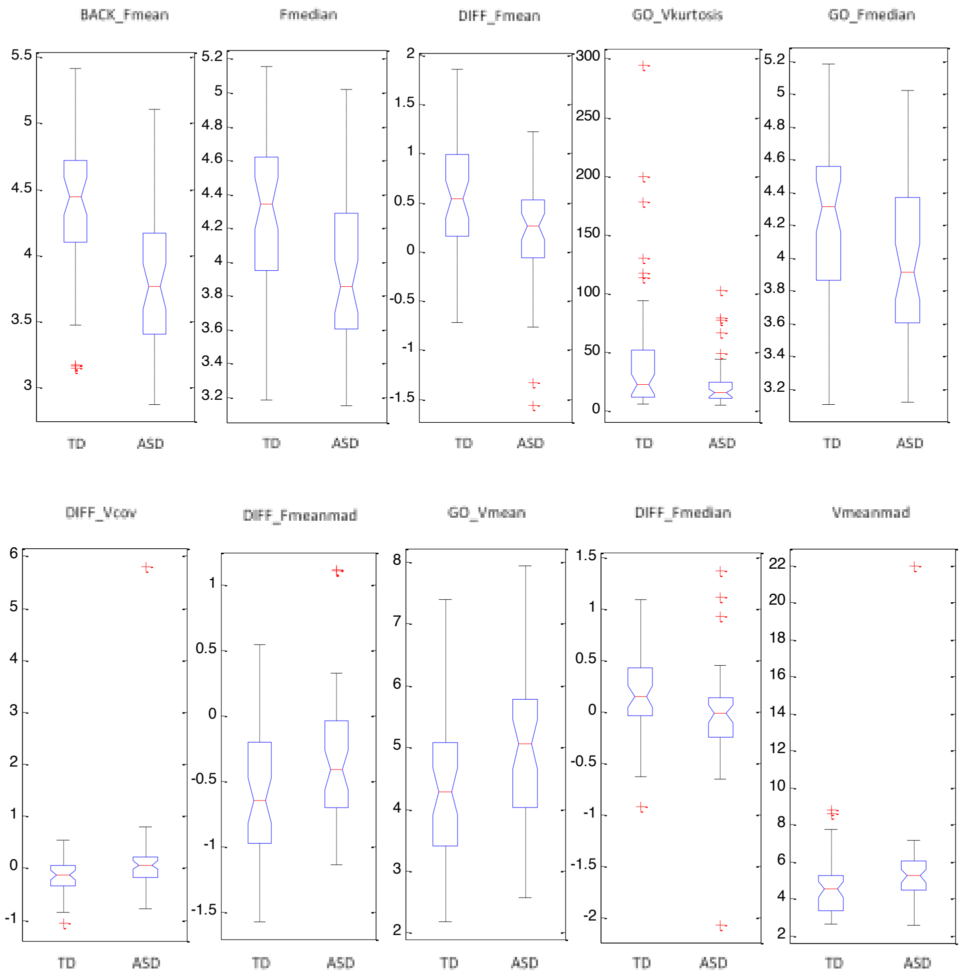

Figure 4-10. Boxplots of the top ten features ranked by F-values using the ANOVA test.

4.6.4 Main Takeaways from the Results

Results from this usability study indicated that the Hg system was acceptable to the study participants. The participants did not face any difficulty in using the system. All participants completed the whole session. However, more attractive tasks and a wide variety of fine motor tasks are still needed to develop in order to retain the participants' attention, especially in a long-term study.

The correlation analysis indicated that there existed medium to large relationships between several proposed performance metrics and the VMI scores, such as task score, grip force and position error. Though movement metrics, movement speed and speed variation, were found to only slightly correlate to the VMI scores, they showed significant influence on the virtual task performance. These results suggested that the proposed metrics could be useful to quantify the fine motor skills, which might assist the fine motor skill assessment in an efficient and objective way.

The performance analysis demonstrated that by practicing on the virtual tasks using Hg, participants in both the TD and ASD groups achieved higher scores on both the VMI Motor Coordination test and virtual tasks in the post-test. Since VMI scores are measures of the real-world motor skills, it is promising to note the potential of skill transfer in real world, which represent an important avenue of future research into generalizability. Both groups also showed improvements in grip force control and hand movement control, considering the increased grip force, and decreased force variation, position error and speed variation. While the TD group could apply proper grip force from the beginning, the ASD group first applied smaller grip force and then gradually increased the applied force after practicing more virtual tasks. Both groups decreased in grip force variations, which suggested that they were able to maintain stable grip force in the post-test. In addition, both groups decreased in average position errors, which imply that they were more likely to move along the optimal paths. The ASD group was found to move faster than the TD group and increased the movement speed considerably while significantly reducing speed variation in the post-test, which suggested that the ASD group was able to perform the fine motor tasks more smoothly after practicing with Hg.

The analysis on the fine motor pattern of children with ASD indicated the effectiveness of using fine motor information for ASD identification, and achieved up to 80% accuracy using machine learning approaches. The results revealed the differential fine motor patterns were related to the grip force and movement speed of children with ASD, supporting the notion that motor differences can be a predictor for ASD diagnosis. It is worth noting that the Grip Force data that have not been sufficiently analyzed in existing studies were showed to contain most useful information to improve classification accuracy.

4.7 Conclusion and Future Work

Many children with ASD experience deficits in fine motor skills as compared to their typically developing peers. However, relatively less research has addressed the fine motor deficits of children with ASD, especially by using advanced technology. Among the few existing studies that explore the fine motor abilities of children with ASD, little has been done to assess the fine motor skills in both hand motion and grip control within a virtual environment using haptic guidance. Considering the usefulness of haptic immersion as well as the importance of grip control in addressing fine motor impairment, we developed a novel haptic-gripper system (Hg) that was able to provide virtual fine motor tasks with real-time feedback for practicing precision grip control and steady motion, as well as automatically record the quantitative data for performance analysis. We conducted a usability study to evaluate the acceptability of Hg among children with ASD and TD children and explore the usefulness of the fine motor information for ASD identification. The study results indicated that Hg can attract the participants and was acceptable among participants who could quickly understand how to perform them. Medium to strong relationships were found between most proposed performance metrics and the VMI scores or virtual task scores. Participants in both group achieved higher scores on both the VMI Motor Coordination test and virtual tasks, and performed more steadily and smoothly on the post-test tasks. In addition, our preliminary findings revealed that grip force and movement speed data contained the most useful information to improve the accuracy of ASD identification. Participants with ASD tended to move faster and apply smaller grip force than their TD peers. This is consistent with Johnson et al. [40], who found that children with ASD had significantly higher movement velocities in handwriting tasks, and by Harden et al[77], who identified lower grip strength of individuals with ASD. These findings lend support to the promising potential of our system for fine motor skill analysis and training for individuals on the autism spectrum, which might expand the accessibility of efficient fine motor interventions.

Although encouraging, our results should be interpreted within the context of several important limitations. The small sample size of the study and the absence of a control group put limits on the generalizability of the results, especially the improvement observed in the VMI scores for ASD participants. It is also not clear whether the observed improvement will be permanent or will require many practice sessions to achieve a long-lasting improvement. In addition, a further investigation of effective and robust performance metrics is needed. In the future, a more systematic multi-session study involving larger sample sizes, a matched control group, more fine motor tasks of varying complexities will need to be designed to meet the needs of users with different fine motor impairments. In spite of these current limitations, we believe that the presented virtual haptic system is one of the first systems of its kind that allows fine motor tasks involving controlled movement of both finger and hand and the presented usability study is the necessary first step to demonstrate its potential in future fine motor intervention for children with ASD.

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CHAPTER 5

A COMPARATIVE ANALYSIS OF THREE CONTROL ARCHITECTURES FOR COLLABORATIVE HAPTIC VIRTUAL ENVIRONMENTS

5.1 Abstract

Collaborative haptic virtual environments (CHVEs) enable haptic interaction between remote users who can perform collaborative tasks in the shared virtual space. The nature of CHVEs requires stable data synchronization of remote CHVE applications over network to achieve consistency in cooperation. In this chapter, three control architectures for maintaining data coherency, namely centralized control architecture, distributed control architecture and wave variable based control architecture, are introduced. In order to compare the performance of these three control architectures with regard to the network delay, a simplified CHVE with the user model was simulated using MATLAB. The experimental results indicated that the centralized control architecture and the wave variable based control architecture have better performance with regard to the frequency response, the position error and the force rendering. With a great time delay, the wave variable based control architecture would outperform the centralized control architecture.

5.2 Introduction

Collaborative haptic virtual environments (CHVEs), in which multiple users can interact within a shared virtual environment with their haptic interfaces over the network, has a wide range of promising applications, including surgical training [1], networked games and haptic-enabled rehabilitation [2]. However, the implementation of CHVEs remains a research challenge because the network-based data communication suffers from delay, packet loss and limited communication bandwidth, which might degrade the stability and performance of CHVEs.

The use of virtual couplings is a way to maintain the stability of haptic interaction independent of both human grasp impedance and the complexity of the virtual environments [3-5]. A virtual coupling is an artificial connection between the haptic display and the virtual environment that can decouple the haptic device control from the virtual environment generation. In this chapter, we first investigated the use of virtual couplings in the centralized control architecture and the distributed control architecture. In the centralized control architecture, each client's haptic display positions are coupled to the shared virtual object maintained at the server using virtual couplings. In the distributed control architecture, each client owns a local copy of the virtual object and these copies are coupled using virtual couplings. Next, we investigated the use of the wave variable control method to implement the virtual couplings in the distributed control architecture. Wave variables have been used to support stable teleoperation and could guarantee stability under arbitrary time delays [6, 7]. We transmitted wave variables instead of the power variables in the distributed control architecture, expecting to increase the stability limit for large time delays.

5.3 Control Architectures for a Simplified CHVE

To simplify the modelling and analysis, a simplified single-axis two-user CHVE was used in this study. Figure 5-1, Figure 5-2, Figure 5-3 illustrate the three control architectures for this simplified CHVE respectively. In this model, two remote users collaboratively move a virtual object along the x axis. The copies of the virtual object are represented by "O", while the virtual haptic handles are represented by "H1" and "H2". The virtual couplers between the virtual object and the haptic handles are represented by K_1 , B_1, K_2 and B_2. Each user controls the position of the virtual haptic handles, which is regarded as the input to move the virtual object. The interaction force (F_1, F_2) between the virtual haptic handle and the virtual object is the output for the user.

5.3.1 Centralized Control Architecture

In the centralized control architecture, a server application collects and processes the data acquired from all the connected client applications, and then propagates the updated data to client applications. In a CHVE, the major task of a server application is to synchronize the status of the virtual objects, which are collaboratively manipulated by remote users. Each user can manipulate the virtual object via a local haptic device. The user manipulation data, such as position and velocity, are sent to the server for computing the new status of the virtual object. Then each client computes the force that its owned haptic device should render based on the updated data received from the serve, and displays the new status of the virtual object on the local computer.

Figure 5-1 shows a two-user model using the centralized control architecture. The client sends the position data of the handle 2 to the server. The server computes and updates the position of the virtual object. Then the server and the client independently compute the interaction force using the updated data. The model can be described by:

$$\begin{gathered}
F_1 = K_1(x_0 - x_1) + B_1(\dot{x}_0 - \dot{x}_1) \\
\overline{x_2} = x_2(t - T_2) \\
m\ddot{x}_0 = -F_1 + K_{12}(\overline{x_2} - x_0) + B_{12}(\overline{\dot{x}_2} - \dot{x}_0) - B_d\dot{x}_0 \\
F_2 = K_2(\overline{x_0} - x_2) + B_2(\dot{\overline{x_0}} - \dot{x}_2) \\
\overline{x_0} = x_0(t - T_1)
\end{gathered} \tag{5-1}$$

where T_1 and T_2 represents the network communication delays between the server and the client, $\overline{x_2}$ is the received position data of handle 2 at the server side, $\overline{x_0}$ is the received position data of the virtual object at the client side, B_d is the damping to avoid drifting when users are not in contact.

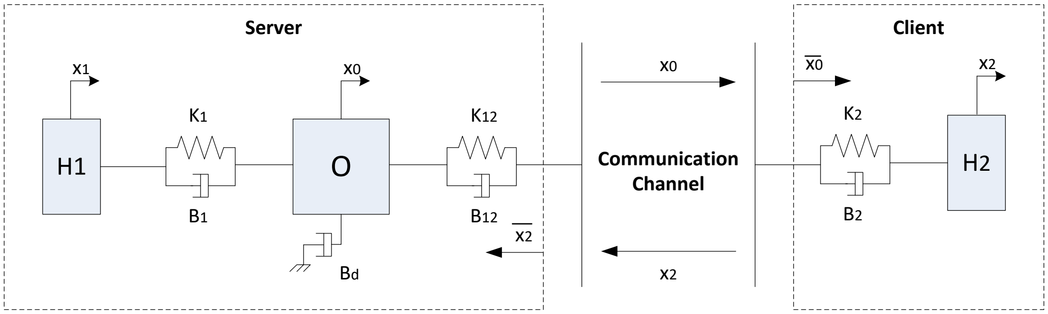


Figure 5-1. The centralized control architecture.

5.3.2 Distributed Control Architecture

In the distributed control architecture, all connected applications runs a complete copy of the shared virtual environment. Each application multicasts the status information of the shared virtual object to all other connected applications. The copies of the shared virtual object are connected by the spring-damper virtual couplers to avoid position drift. Each application individually computes and updates the status of the local copy of the shared virtual object, and render appropriate forces.

Figure 5-2 shows a two-user model using the distributed control architecture. Each application has a copy of the virtual object. The virtual couplers represented by *K* and *B* are used for the two copies to track each other and transmit forces between them. Thus the position of the virtual object depends on the local handle's position and the position difference of the two copies. The model can be described by:

$$\begin{gathered}
F_1 = K_1(x_{01}-x_1) + B_1(\dot{x}_{01} - \dot{x}_1) \\
\overline{x_{02}} = x_{02}(t - T_2) \\
\frac{m}{2}\ddot{x}_{01} = -F_1 + K(\overline{x_{02}} - x_{01}) + B(\dot{\overline{x}}_{02} - \dot{x}_{01}) - B_d\dot{x}_{01} \\
F_2 = K_2(x_{02}-x_2) + B_2(\dot{x}_{02} - \dot{x}_2) \\
\overline{x_{01}} = x_{01}(t - T_1) \\
\frac{m}{2}\ddot{x}_{02} = -F_2 + K(\overline{x_{01}} - x_{02}) + B(\dot{\overline{x}}_{01} - \dot{x}_{02}) - B_d\dot{x}_{02}
\end{gathered} \tag{5-2}$$

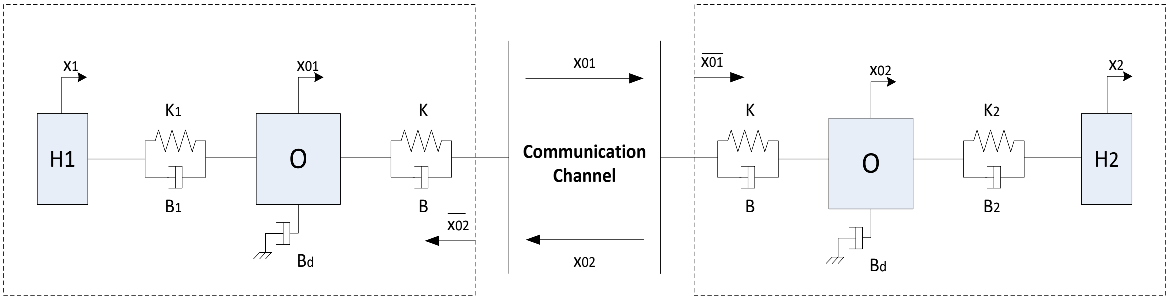


Figure 5-2. The distributed control architecture.

5.3.3 Wave Variable Based Control Architecture

Wave variable based control architecture can guarantee system stability under arbitrary time delays of the communication channel. In this architecture, wave variables(u, v) that encode a pair of power variables, velocity$(\dot{x})$ and force(F), are transmitted across the communication channel. The wave variables are computed as follow:

$$u = \frac{b\dot{x} + F}{\sqrt{2b}}, \qquad v = \frac{b\dot{x} - F}{\sqrt{2b}} \tag{5-3}$$

where *b*, called wave impedance, is a positive constant that determines the transformation behavior.

Figure 5-3. shows a two-user model using the wave variable based control architecture. Each application has a wave transformation interface to encode the force command (F_{t1}, F_{t2}) into the forward wave and simultaneously get a velocity feedback signal $(\dot{x}_{o1d}, \dot{x}_{o2d})$ from the returning wave. For example, on the side of the application 2, the desired velocity $\dot{x}_{o2d}$ can be decoded from the wave transformation as follow:

$$\dot{x}_{02d} = \frac{\sqrt{2b}\,\bar{u}_1 - F_{t2}}{b}, \qquad \bar{u}_1 = u_1(t - T_1) \tag{5-4}$$

The force that the virtual coupler generates to track the desired velocity $\dot{x}_{o2d}$ is:

$$F_{t2} = K(x_{02d} - x_{02}) + B(\dot{x}_{02d} - \dot{x}_{02}) \tag{5-5}$$

The designed velocity and the force depend on each other. By combining the above two equations, we can get:

$$\dot{x}_{02d} = \frac{\sqrt{2b}\,\bar{u}_1 + B\dot{x}_{02} + K(x_{02} - x_{02d})}{B + b} \tag{5-6}$$

and the return wave is :

$$v_2 = \frac{b\dot{x}_{o2d} - F_{t2}}{\sqrt{2b}} = \bar{u}_1 - \sqrt{\frac{2}{b}}F_{t2} \tag{5-7}$$

Similarly, on the side of the application 1, we can get:

$$\begin{gathered}
\dot{x}_{01d} = \frac{\sqrt{2b}\,\bar{v}_2 + B\dot{x}_{01} + K(x_{01} - x_{01d})}{B + b} \\
F_{t1} = K(x_{01} - x_{01d}) + B(\dot{x}_{01} - \dot{x}_{01d}) \\
u_1 = \frac{b\dot{x}_{01d} + F_{t1}}{\sqrt{2b}} = \bar{v}_2 + \sqrt{\frac{2}{b}}F_{t1}
\end{gathered} \tag{5-8}$$

Thus, the model can be described by:

$$\begin{gathered}
F_1 = K_1(x_{01} - x_1) + B_1(\dot{x}_{01} - \dot{x}_1) \\
\frac{m}{2}\ddot{x}_{01} = -F_1 - F_{t1} - B_d\dot{x}_{01} \\
F_2 = K_2(x_{02} - x_2) + B_2(\dot{x}_{02} - \dot{x}_2) \\
\frac{m}{2}\ddot{x}_{02} = -F_2 + F_{t2} - B_d\dot{x}_{02}
\end{gathered} \tag{5-9}$$

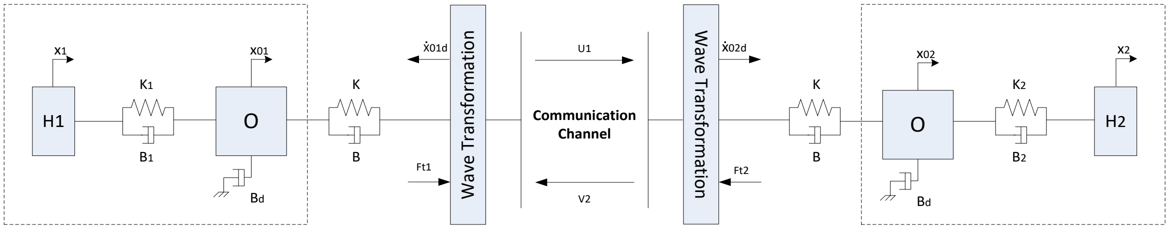


Figure 5-3. The wave variable based control architecture.

5.4 Experiments

A simplified CHVE with these three control architectures was simulated using MATLAB to evaluate the performance of these control architectures in terms of the position error and the force rendering under different network delays. The CHVE consists of a target and a cube. The target moves along x axis and is controlled by a sine function $x = 4\sin(wt)\ (cm)$. Two users collaboratively move the cube to track the target and try to align the center of the cube with the target. One user stays at the left side of the cube and can only push the left side of the cube, while the other user stays at the right side and can only push the right side of the cube.

5.4.1 User Hand Model

To complete the task in this CHVE, the user was supposed to control the haptic handle with one hand to generate the position input, and to adjust the position input according the real-time error between the target and the cube. Therefore, the user hand can be modeled with a proportional-integral (PI) controller [8]:

$$F_h = K_p(x_t - x_c) + K_i \int_0^t (x_t - x_c)dt \tag{5-10}$$

where K_p and $K_i$are the proportional gain and the integral gain of the user hand respectively, and F_h is the output hand force to adjust the position input.

In the experiments, we assumed that both users were in contact with the cube all the time. When the user pushed the cube, a force feedback (F_1 for user 1 and F_2 for user 2) was applied on the haptic handle. Thus the handle position could be computed by:

$$\begin{gathered} m_h\ddot{a}_h = F_h + F \\ x_h = \int_0^t \ddot{a}_h dt^2 \end{gathered} \tag{5-11}$$

where F is the force feedback F_1 or F_2, and $x_h$is the handle position x_1 or x_2. Because one user can only move the cube toward one direction, additional restrictions were added to the user hand model to make the haptic handle always touch one side of the cube.

5.4.2 System Parameters

The system parameters chosen for the experiments are shown in Table 5-1. The value for the mass of the haptic handle (H_1, H_2) was set to the real weight of the Haptic Gripper. The values of the proportional gain (K_p) and the integral gain (K_i) of the user hand were chosen to provide appropriate response speed. The values for the stiffness (K_1, K_2, K_{12}) and damping (B_1, B_2, B_{12}) of the virtual coupler between the haptic handle and the cube were set to the maximum values of the Geomagic Touch Haptic device can provide. Considering that the maximum force that the Geomagic Touch Haptic device can render is 3.3 N, the mass of the cube (m_0) was set to a small value so that the user can move the cube using small force. The value of the damping (B_d) was chosen to make the cube stop moving quickly. The values of K and B were chosen to maintain small position error between the copies of the cube. The wave impedance b was set as the same value of B to reduce wave reflection. Two values of the wave impedance b were used to evaluate how the wave impedance b affects the transmission behavior.

Table 5-1. System parameters used in the experiments.

Symbols	**Values**
m_0	$1\ kg$
H_1, H_2	$0.035\ kg$
K_p	$2\ N/cm$
K_i	$1\ N/cm$
K_1, K_2, K_{12}	$5\ N/cm$
B_1, B_2, B_{12}	$0.03\ N \cdot s/cm$
B_d	$1\ N \cdot s/cm$
K	$40\ N/cm$
B	$1\ N \cdot s/cm$
b	$1\ N \cdot s/cm\ , 5\ N \cdot s/cm$

5.4.3 Experimental Procedure

Previous studies have shown that the average network transmission delay of CHVE was below 200 ms

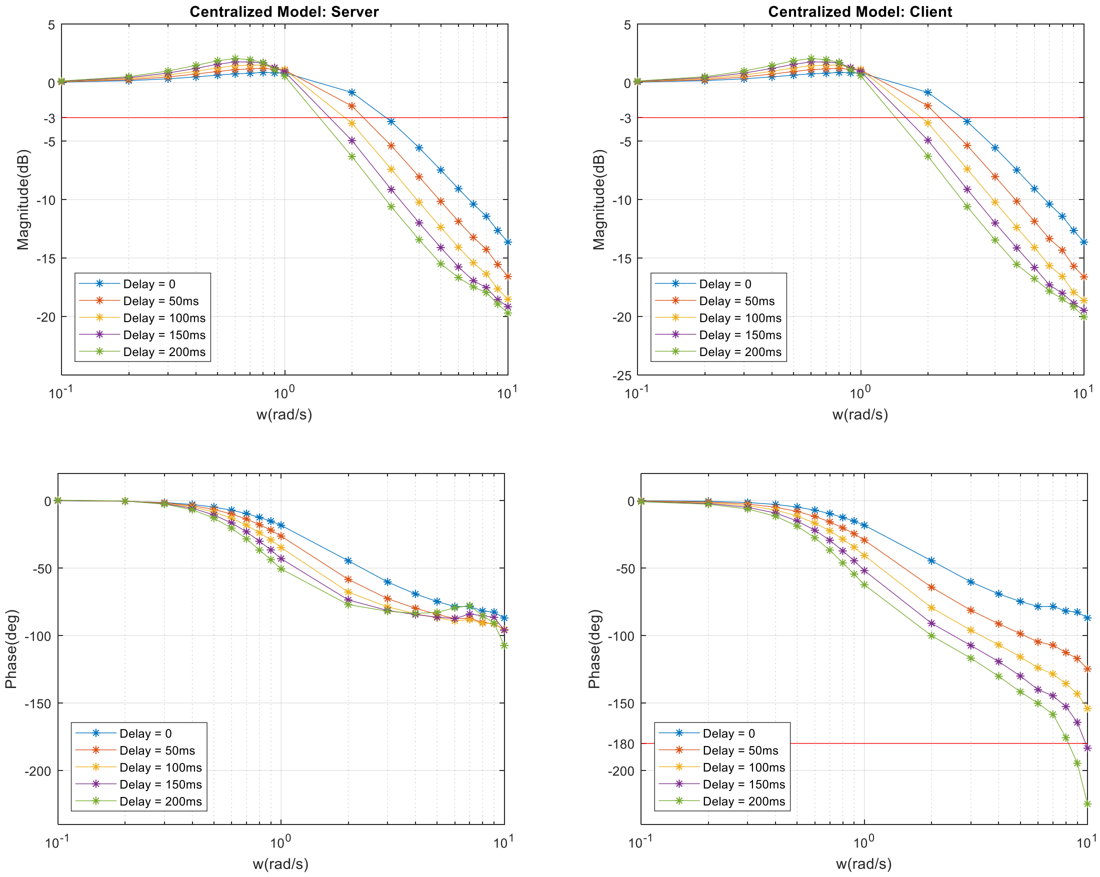
[9]. Thus, in the experiments, these control architectures were tested with one-way constant time delay from 0 to 200 ms in steps of 50 ms.

During the experiments, all the models were simulated with a fixed update rate 1000 Hz, and the position data and the force data were also collected at the same rate. Based on these data, the frequency responses of three models with regard to different time delays were obtained. To evaluate the position coherence, the RMS position error between the target and the cube, and between cubes on server and client sides were computed. To evaluate the force rendering, the mean interaction force was computed.

5.5 Results and Discussions

5.5.1 Frequency Response

We tested three control models with regard to the movement frequency (w) of the target. Figure 5-4, Figure 5-5 and Figure 5-6 respectively show the frequency responses of these models.



Centralized Model: Server

Centralized Model: Client

Figure 5-4. The bode diagrams of the centralized control model.

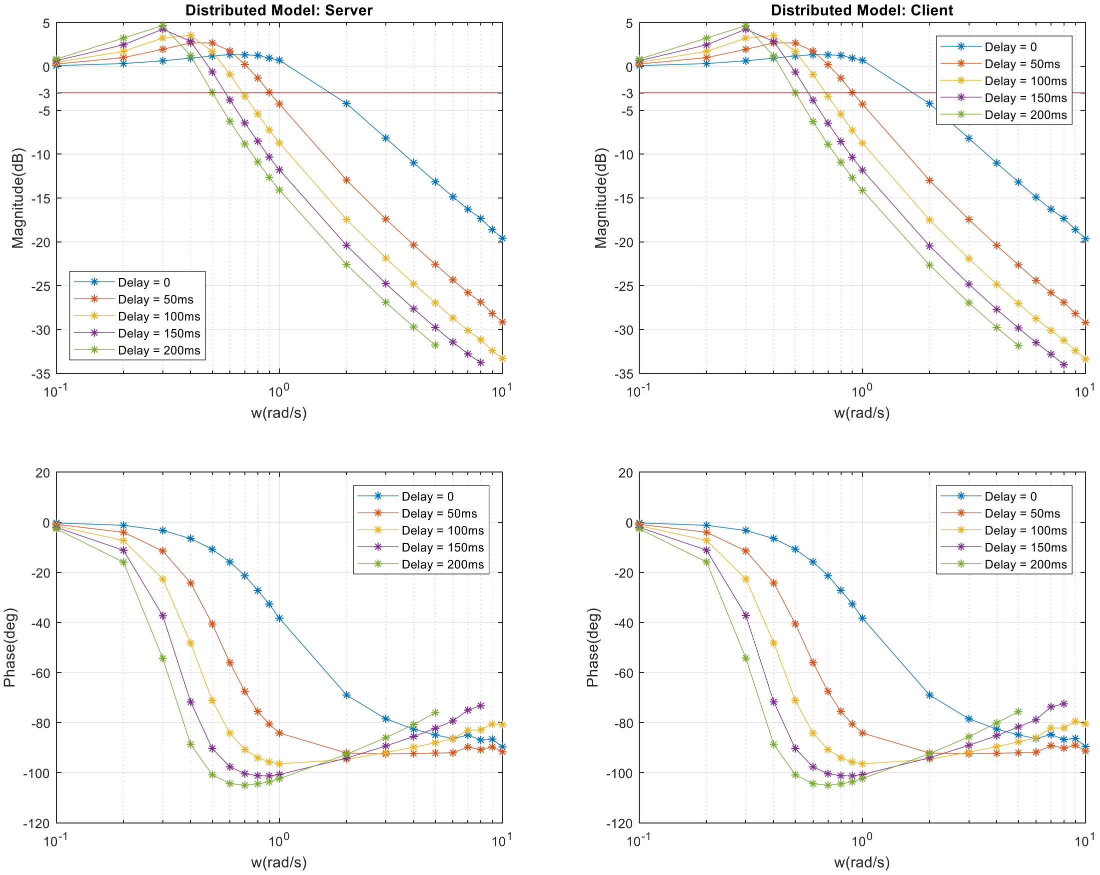
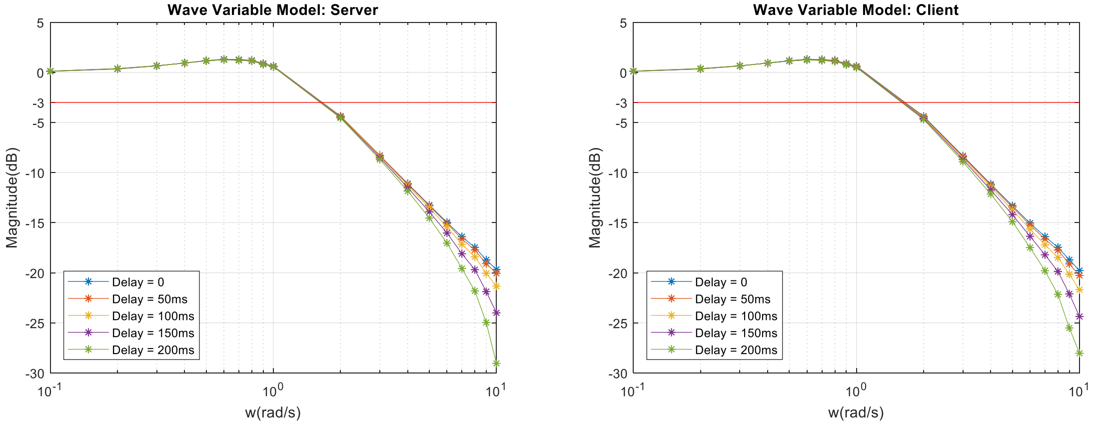


Figure 5-5. The bode diagrams of the distributed control model.



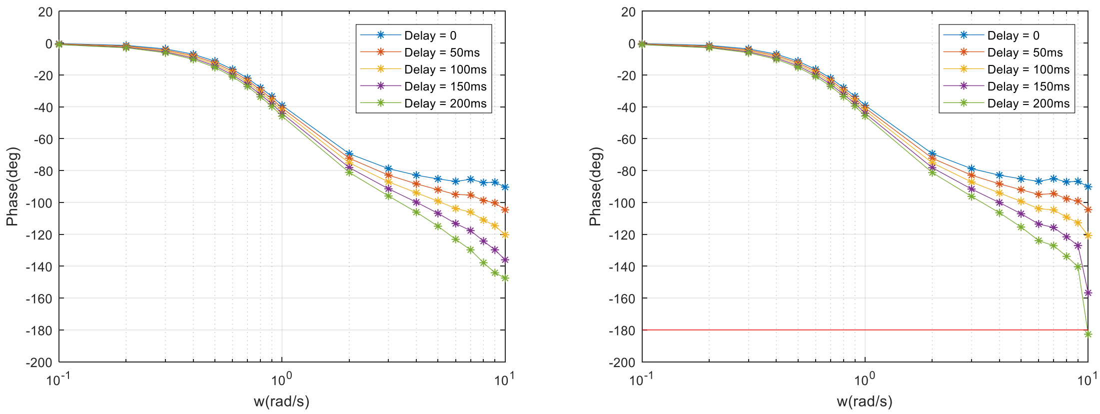


Figure 5-6. The bode diagrams of the wave variable based control model (b = 1).

For all the models, the bandwidth decreases as the time delay increases. Compared to the other two models, the centralized control model has the best bandwidths. When the time delay is 0, the bandwidth of the centralized control model is close to 3 rad/s, while those of the distributed and wave variable based control models are below 2 rad/s. As the time delays increases, the bandwidth of the distributed control model drops below 1 rad/s, while the other two stay above 1 rad/s.

As for the phase response, the phase difference between the cube and the target increases as the delay. The centralized control model and the wave variable based control model have lower phase lag than that of the distributed control model. Because of the model symmetry, the distributed control model and the wave variable based control model have the similar phase responses on the server and client. However, the client of the centralized control model has larger phase lag than its server due to the time delay. At the high frequencies with larger time delays, the amplitude ratio of the cube and the target would drop below -20 dB. It is difficult for the cube to track the trajectory of the target, especially for the distributed control model.

5.5.2 Position Coherence

Position coherence is important for collaborative games, in which players control the same object together. According to the frequency response, these control models will not track the target well when the frequency is above 2 rad/s, and thus we only compare the performance of these models for maintaining the position coherence within the small frequency range (< 2 rad/s). First, the RMSE position errors between the target and cube on the server and client for these models are compared (Figure 5-7, Figure 5-8, Figure 5-9).

The centralized control model and the wave variable based control model have lower RMSE position errors, compared to the distributed control model. Due to the time delay, the client in the centralized control model has larger position errors than its server. As the delay increased, the position error for the distributed control architecture increased quickly which indicated the difficulty for the cube to track the target under the condition with a higher delay. At the high frequencies, the cube is unable to track the target and would move slightly around a fixed position. Thus the position errors for all the high frequencies would be similar.

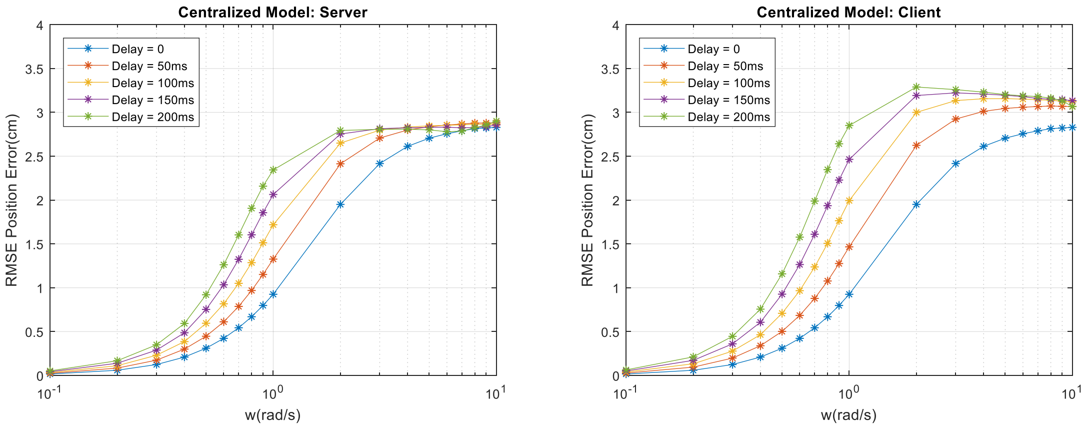


Figure 5-7. The RMSE position errors between the target and the cube for the centralized control model.

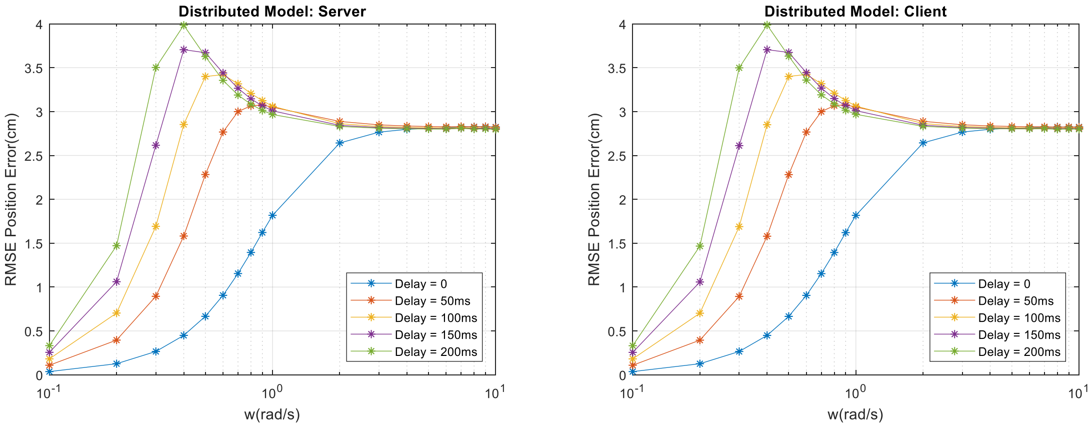


Figure 5-8. The RMSE position errors between the target and the cube for the distributed control model.

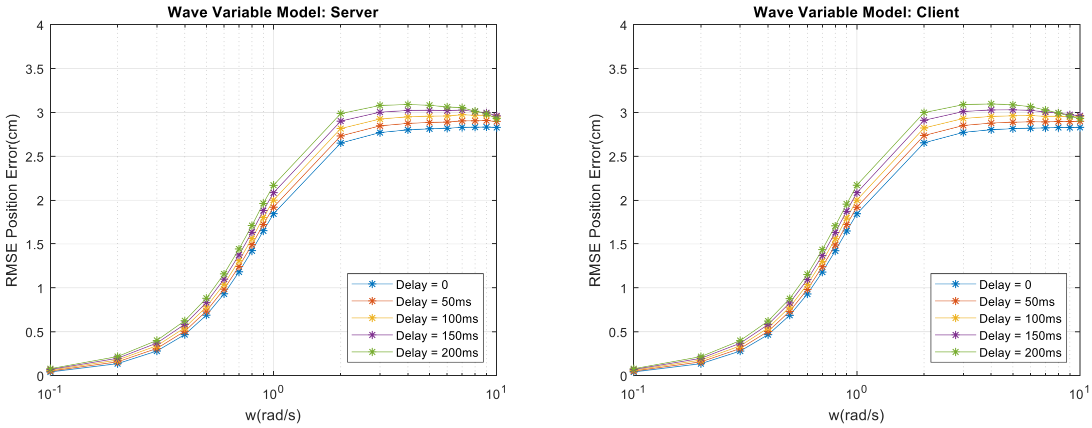


Figure 5-9. The RMSE position errors between the target and the cube for the wave variable based control model.

We also computed the RMSE position errors between the cube of the server and the cube of client for three models (Figure 5-10, Figure 5-11, Figure 5-12). The centralized control model and the wave variable based control model still have better performance. It is reasonable that the centralized control model has the good performance, because the client cube copies the position of the server cube. By increasing the wave impedance *b*, the RMSE position errors between two cubes could be reduced.

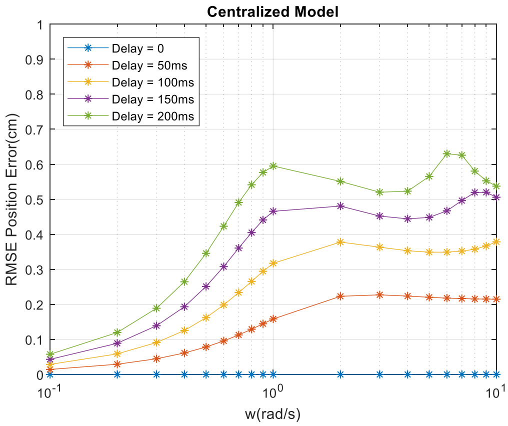


Figure 5-10. The RMSE position errors between the cube of the server and the cube of client for the centralized control model.

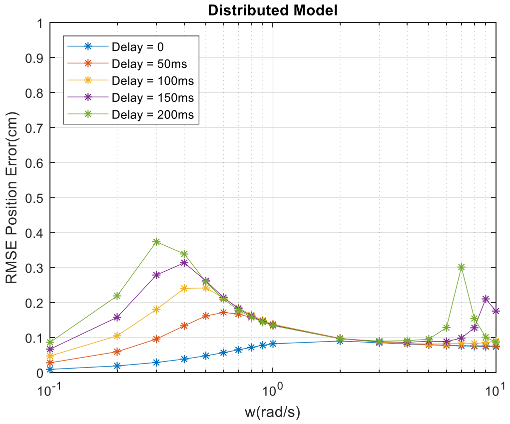


Figure 5-11. The RMSE position errors between the cube of the server and the cube of client for the distributed control model.

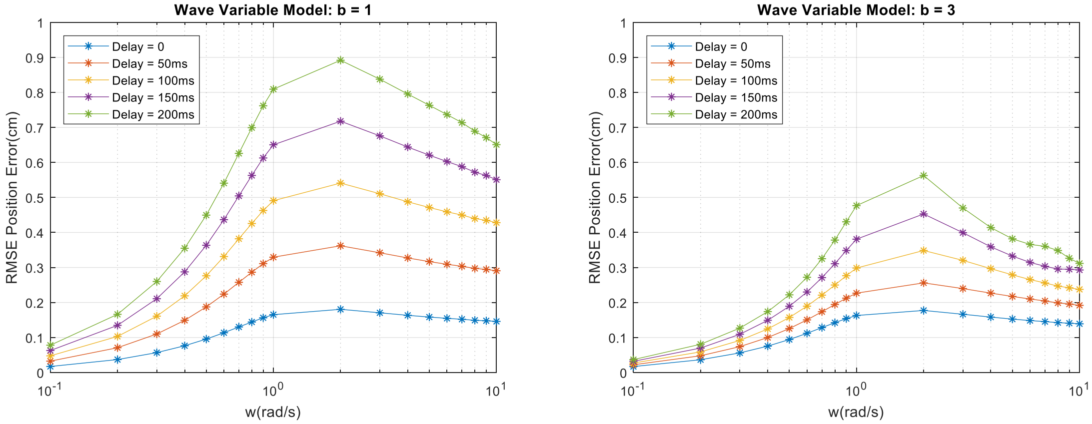


Figure 5-12. The RMSE position errors between the cube of the server and the cube of client for the wave variable based control model.

5.5.3 Force Rendering

The force feedback the system applies on the user's hand can affect the user's manipulations. Figure 5-13, Figure 5-14, and Figure 5-15 show the mean force feedback F1 and F2 for the models.

Compared to the slow increase found in the centralized control model and the wave variable based control model, the distributed control model has greater increase with the increased time delay or target frequency. Though increased wave impedance *b* can reduce the position error, it will increase the force variations.

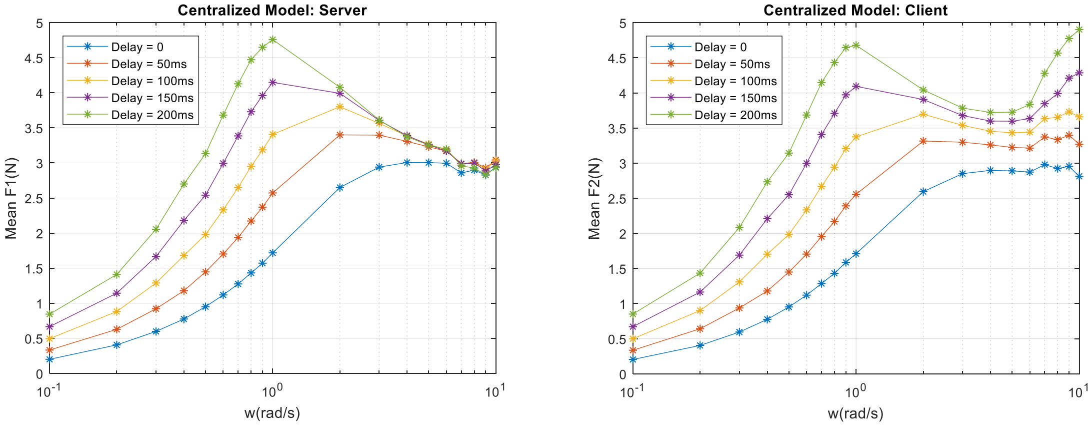


Figure 5-13. The mean force feedback F1 for the server user and F2 for the client user in the centralized control model.

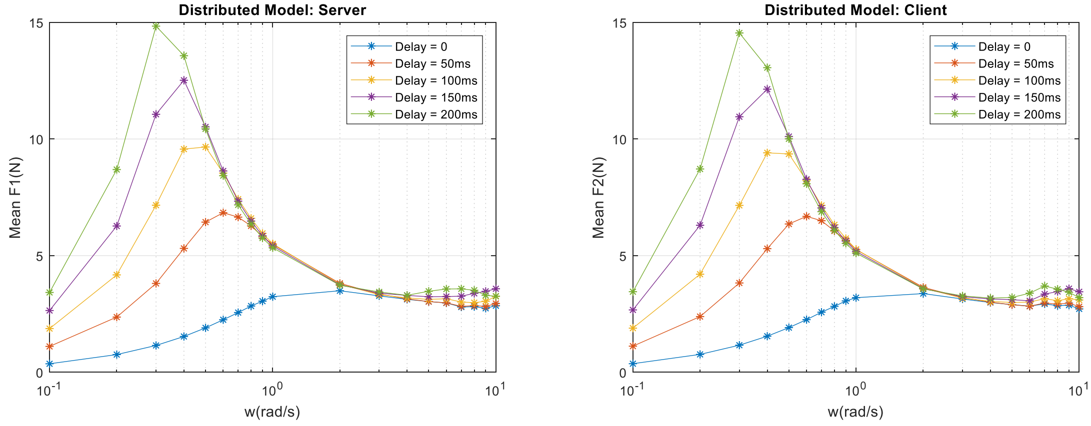
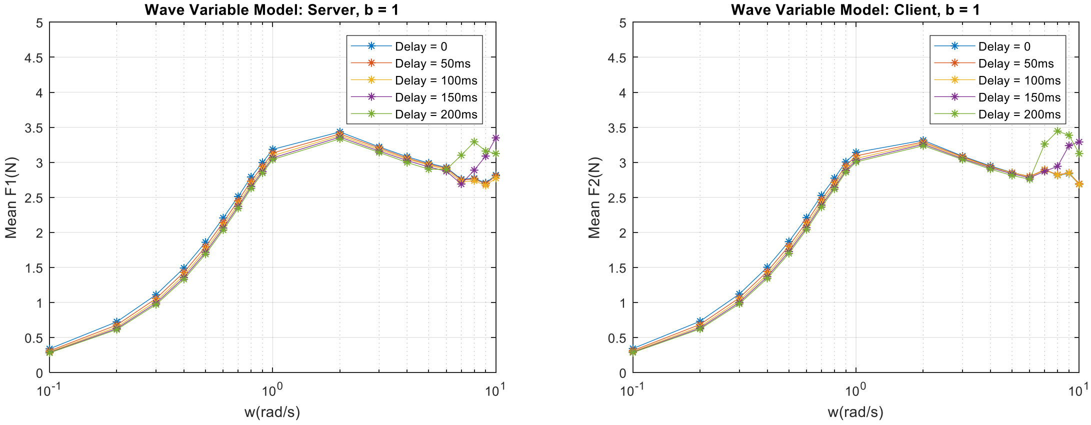


Figure 5-14. The mean force feedback F1 for the server user and F2 for the client user in the distributed control model.



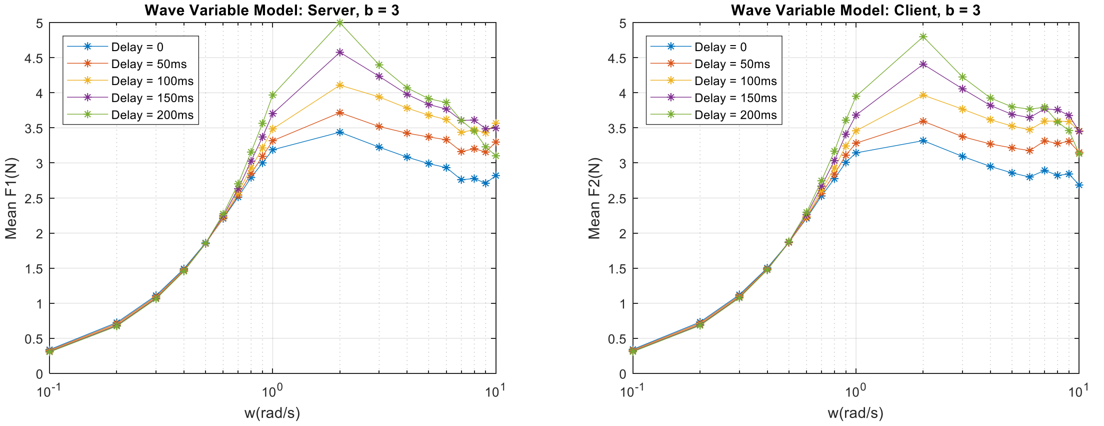


Figure 5-15. The mean force feedback F1 for the server user and F2 for the client user in the wave-variable-based control model.

5.6 Conclusion

The experimental results indicate that the centralized control architecture and the wave-variable-based control architecture have better performance with regard to the frequency response, the position error and the force rendering. As the time delay increases, the wave-variable-based control architecture would outperform the centralized control architecture. The wave impedance *b* can be chosen to maintain lower position error and appropriate force feedback.

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CHAPTER 6

C-Hg: A COLLABORATIVE HAPTIC-GRIPPER VIRTUAL REALITY SYSTEM

6.1 Abstract

Computer-assisted systems can provide efficient and engaging ASD intervention environments for children with Autism Spectrum Disorder (ASD). However, most existing computer-assisted systems target only one specific skill deficit (e.g., social conversation skill) and ignore the importance of other skills, such as motor skills, that could also impact social interaction. This may hinder generalizability of learnt skills to real-world scenarios. The work presented in this Chapter seeks to bridge this gap by developing a Collaborative Haptic-gripper virtual skill training system (C-Hg). This system includes individual and collaborative games that provide opportunities for simultaneously practicing both fine motor skills (hand movement and grip control skills) as well as social skills (communication and collaboration) and investigating how they relate to each other. We conducted a usability study with 10 children with ASD and 10 typically developing (TD) children (8-12 years), who used C-Hg to play the games. Statistical analyses indicated significant performance improvements of participants in both individual and collaborative fine motor skill training tasks, and significant improvements of collaborative manipulations between partners. Participants with ASD were found to conduct more collaborative manipulations and initiate more conversations with their partners, suggesting more active collaboration and communication of participants with ASD in the collaborative tasks. Results support the potential of our C-Hg system for simultaneously improving fine motor and social skills, with implications for impacts of improved fine motor skills on social outcomes.

6.2 Introduction

Impairments in executive function skills (EF), which include domains such as working memory, flexible thinking, and inhibition of impulses, are commonly reported among individuals with ASD [1-3]. Executive function skills are crucial for effective coordination and completion of tasks, with deficits associated with poor adaptive, academic, and employment outcomes [4, 5] These skills are especially important to multitasking, or the ability to plan, coordinate and complete multiple tasks within a given time period not in a sequential fashion but rather by interweaving task performance by switching back and forth between them [6].

Because of the relevance of EF to so many academic, adaptive, and employment tasks, several recent studies have investigated EF in ASD by using multitasking paradigms [7-9]. Multitasking involves many aspects of EF that may be hard for someone with ASD, such as switching attention between components and practicing flexible thinking. Mackinlay et al. [7] investigated multitasking in 14 children with high-functioning ASD (HF-ASD) and 16 typically developing (TD) controls using a novel task called the Battersea Multitask Paradigm (BMP). The BMP consists of three interwoven tasks (bead sorting, counter sorting and caterpillar) which should be completed within 3 minutes. The authors assessed the cognitive processes underlying multitasking by using a six-stage invariant sequence, proposed by [10], which were Rule learn, Plan, Perform, Plan follow, Monitor and Rule memory. Results indicated that the ASD group generated significantly fewer strategic plans, attempted fewer tasks, and less flexibility in switching between tasks, and that they broke rules more frequently than the TD controls. Rajendran et al. [8] used a modified version of the Virtual Errands Task (VET) [11] to investigate EF and multitasking in 18 adolescents with HF-ASD and 18 TD controls. In VET, participants were required to role-play a lecturer running a set of errands in a university building within 8 minutes. Participants were awarded points for task completion and had points subtracted for breaking rules. Results indicated that the ASD group completed fewer tasks, broke more rules and more rigidly followed the task list in the original order of presentation. Therefore, the authors concluded that inflexible planning, low inhibition, as well as difficulties with prospective memory (remembering to carry out intentions) may underlie multitasking difficulties in ASD. Finally, Hutchison et al. [12] examined EF in relation to basic functional communication (FC) and more complex verbal conversation (VC) skills among 92 children with ASD and 94 TD controls. They reported that metacognition (or "thinking about thinking") was a strong predictor of FC, while the domains of behavioral regulation and inhibition were predictive of VC skills. Therefore, they suggested that targeting EF domains specifically might improve FC and VC skills in children with ASD.

The impact of EF on multitasking and its impact on individuals with ASD becomes more salient when one considers that multitasking is a ubiquitous requirement of everyday activities, including social interactions. Each interaction draws upon not only the need to inhibit impulses, pay attention to cues, remember what has just happened, and plan for what happens next; many also involve motor skills, another common area of deficits for many people on the autism spectrum [13]. Motor skill deficits (including gross motor, i.e., postural control and limb movements; and fine motor, i.e., object control, manual dexterity and visuomotor integration) are incredibly prevalent among children with ASD, estimated to occur in 90% of individuals with ASD across the lifespan [14-18]. Fine motor challenges in children with ASD include trouble with grasping and reaching [19], eye-hand coordination [20], and handwriting skills [21]. These basic tasks, which many people execute almost automatically, likely require extra effort, control, and mental attention from people with ASD.

When thinking about designing intervention paradigms for individuals with multiple areas warranting attention, it follows that focusing on a single area of deficit (e.g., conversation) rather than incorporating multiple integrated targets (e.g., conversation as part of game-playing) may hinder the generalizability of learnt skills to complex real-world activities. In particular, it will be problematic if additional real-word components create added levels of difficulty and complexity that could impact success. Existing literature suggests that teaching motor skills to children with ASD may help create a context for practicing social skills and lead to further social success [18]. For example, Chetcuti et al.[22] conducted a study with 35 children with ASD and 20 TD children to examine the role of social motivation and motor execution factors in object-directed imitation difficulties in ASD. They found that difficulties in object-directed imitation in ASD might be the result of motor execution difficulties, and not reduced social motivation. Srinivasan et al. [23] evaluated the impacts of rhythm, robotic and standard-of-care interventions, on 36 children with ASD (5-12 years of age). They found that socially embedded movement-based contexts are valuable in promoting imitation/praxis, interpersonal synchrony and motor performance. Fulceri et al. [24] applied Artificial Neural Networks (ANNs) to reveal the entire spectrum of the relationship between motor skills and clinical variables. Their findings suggested that poor motor skills were a common clinical feature of preschoolers with ASD, relating both to the high level of repetitive behaviors and to the low level of expressive language. Collectively, these findings suggest that in order to benefit from social skills training, some individuals might also require training in other, related functional domains, like motor skills.

Compared to extensive research focusing on the social deficits of ASD, motor deficits of children with ASD and the influence of motor skills on social skills of children with ASD are relatively underexplored, especially within the context of technological intervention. To address this issue, a training system that can provide social skills practice as well as the fine motor skill practice is needed. In Chapter 2, we have developed a Collaborative Virtual Environment (CVE) to provide social skill training for children with ASD. The CVE system preserves the benefits of virtual reality (VR) systems but also offers the opportunities for flexible and convenient interactions over Internet between remote users. In Chapter 4, we have developed a Haptic-Gripper VR system (Hg) to provide fine motor skill training for children with ASD. Hg took advantages of the haptic device to increase immersion and quality of task performance and thus had the possibility of enhancing the training outcomes. Combining these two systems, we present a collaborative haptic-gripper virtual reality system, called C-Hg, to simultaneously practice social skills (communication and collaboration skills) and fine motor skills (hand movement and grip control skills), and to investigate the impact of fine motor skill improvement on social skill trajectory.

In this chapter, we introduce a collaborative haptic-gripper fine motor skill training system (C-Hg) that can provide carefully designed fine motor skill training tasks in both individual mode and collaborative mode. In the collaborative mode, a Collaborative Haptic Virtual Environment (CHVE) is built to allow remote users to perform haptic interaction through haptic devices. Social communication and collaboration skills are required to successfully implement the fine motor skill training tasks in the collaborative mode. We also present a usability study to explore the usefulness of this system on improving the fine motor skills through individual fine motor tasks, and also to investigate if improved fine motor skills would improve the social communication and collaboration skills of the users.

The rest of the chapter is organized as follows. Section 6.3 presents the system design, which is followed by the usability study in Section 6.4. The results and discussions of the study are presented in Section 6.5. Finally, we summarize the contributions of the work and discuss its limitations in Section 6.6.

6.3 C-Hg System Design

The Collaborative Haptic-Gripper virtual reality system (C-Hg) allows remote users to perform virtual fine motor tasks collaboratively. Figure 6-1, shows the system architecture with the major modules. The user interacts with C-Hg via the *Haptic Gripper*, with which the user can manipulate the virtual objects as well as feel the force feedback. Two basic hand manipulations are provided by the Haptic Gripper. The first one is Movement Manipulation. For example, the user can change the position of the controlled virtual objects by holding and moving the gripper. The second one is Grip Manipulation, which requires the user to squeeze the red plates of the gripper using fingers. This manipulation may change some property of the virtual object (e.g., the size of the object) based on game objectives. The *Haptic Gripper Controller* obtains the grip force data and the hand position data of the user, and sends the data to the *Virtual Task Manager* for updating the states of the virtual objects. The response of the user's manipulation would present to the user in the form of visual, auditory and/or force feedback.

The C-Hg system provides an individual training mode as well as a collaborative training mode. In the individual training mode, the user performs the tasks alone to practice individual fine motor skills. In the collaborative training mode, two users complete tasks in a cooperative manner that can foster their communication and collaboration skills at the same time. In Chapter 5, we have tested the performance of three different control architectures: a centralized control architecture, a distributed control architecture, and a wave-variable-based control architecture. We found that the centralized control architecture and the wave-variable-based control architecture have better performance with regard to frequency response, position error and force rendering. For the usability study, we used the centralized control architecture because the study was conducted in a LAN environment with small network delays. When two users selected the collaborative mode and wanted to play together, their applications were connected. One of these applications would play the role of a server to manage all input data to update the task states and to synchronize the updated task states on both applications.

The virtual tasks of C-Hg system were carefully designed (as discussed later) to assess and train the user's fine motor skills that require the coordination of the finger, hand, arm and eye. We have designed three types of fine motor virtual tasks separately focusing on Grip Manipulation ("*Curling*" task), Movement Manipulation ("*Go, Wheel!*" task), and complex manipulation that involves both Grip Manipulation and Movement Manipulation ("*Prize Claw*" task and "*Green Path*" task). These tasks are designed with the objective of providing both fine motor manipulation and collaboration opportunities through embedded rules that are needed to be adhered for success. The *Data Log* records specific user data and task data, which are time-synchronized for offline processing and analysis.

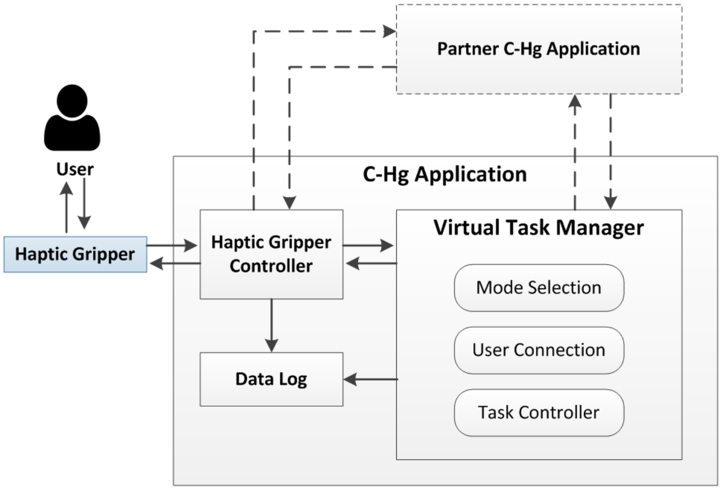

Figure 6-1. The C-Hg System Architecture.

6.3.1 Grip Task: *Curling*

Grip manipulation skill is frequently needed in children's daily activities, such as handwriting and using a keyboard. Studies have shown that children with ASD might exhibit inappropriate grip force adjustment, and greater grip force variability compared to their TD peers [25]. The "*Curling*" task was designed to practice grip control capability.

As shown in Figure 6-2, the *Curling* task requires the user to move a curling stone with the goal to stop it within a circular target with rewards. The user applies controlled pressure on the gripper in order to move the curling stone along the y axis, and releases the gripper to make it decelerate to a stop. The motion equations of the curling stone are:

$$a = \frac{F - f}{m} \tag{6-1}$$

$$y_{curr} = y_{last} + v_{last} \times \Delta t + \frac{1}{2} \times a \times \Delta t^2$$

$$v_{curr} = v_{ast} + a \times \Delta t$$

where F is the grip force the user applies on the gripper, f is the dynamic friction, m is the mass of the curling stone, y_{last} and v_{last} are the last position and velocity of the curling stone, respectively, and y_{curr} and v_{curr} are the new position and velocity of the curling stone, respectively. The user should estimate the stopping distance of the curling stone according to its velocity, and carefully adjust the grip force to make the curling stone remain within the target area. When the user successfully places the curling stone within the target, or when the user moves the curling stone over the target, the target disappears and a new one appears at a random location along the *y* axis. To enhance user immersion, a constant resistance force feedback is generated through the haptic device to simulate the feeling that the user may get when pushing the curling stone.

In the collaborative mode, two users move the curling stone together, but along two perpendicular axes. As shown in Figure 6-2, the Player A can only move it along the *x* axis, while the Player B can only move it along the *y* axis. Their joint force determines the movement direction and speed of the curling stone. One user cannot move the curling stone to the target without the help of the partner. For example, in the collaborative task of Figure 6-2, if Player A and Player B apply the same pressure on the gripper at the same time, the curling stone can move straight towards the target. But if Player A applies bigger pressure or only Player A applies pressure on the gripper, the curling stone would move towards the left side of the target (close to the *x* axis). Therefore, both players have to discuss when and who should grip, and how much pressure to use when controlling the curling stone together. The best manipulations for getting more rewards have to be negotiated and performed in a cooperative way.

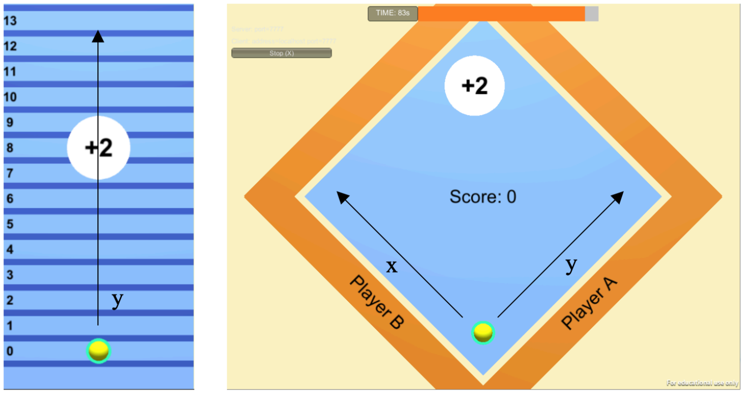

Figure 6-2. The grip task *Curling* in the individual mode (left) and in the collaborative mode (right).

6.3.2 Movement Task: *Go, wheel!*

Children with ASD have shown differences in fine motor movements from their TD peers regarding the movement speed, movement adjustment and eye-hand coordination [26, 27]. The "*Go, wheel!*" task was designed for the user to practice movement control.

In the individual "*Go, Wheel!*" task, the user is required to pull a rolling wheel to the left side or to the right side to collect gold coins while avoiding rocks on the road. Once the wheel is pulled to one side or hits a rock, it falls to the ground at a certain speed unless the user successfully pulls it back. The tilting angle of the wheel is controlled by the following equations:

$$\alpha_{curr} = \begin{cases} \arcsin \dfrac{d \times \sin \alpha_{last} + disp_x}{d}, & if \quad disp_x > 0 \\ \alpha_{last} + \alpha_0 \times \Delta t, & if \quad \alpha_{last} \neq 0 \; and \; disp_x = 0 \end{cases} \tag{6-2}$$

where $disp_x$ is the displacement of the user's hand movement along the x axis, d is the diameter of the wheel, α_0 is the falling angle per unit of time, the α_{last} is the tilting angle of the wheel at the last time instant, and α_{curr} is the new tilting angle of the wheel. When the wheel is falling to one side or the user is pulling the wheel, a spring force feedback is generated to simulate the pulling force, which can prompt the user to take actions.

In the collaborative mode, two users control the wheel together, but each user can only pull the wheel to one side. As shown in Figure 6-3, Player A can only pull it to the right side, while the Player B can only pull it to the left side. When they want to get a gold coin on the right side, only Player A can pull the wheel to the right side to get it, and only Player B can pull the wheel back to prevent it from falling on the ground. Thus, each manipulation for catching a golden coin requires collaboration of two players, and they should pay attention to the partner's action and help each other at the right time in order to keep the wheel upright. The task also requires communication to decide which coin to catch, and when and who to pull the wheel, since the golden coins can come from either left side or right side, and in different speeds. If two players pull the wheel to the opposite sides, they would fail to get the coin. Therefore, two players have to coincide their manipulations through communication, in order to get higher scores.

Figure 6-3. The movement task *Go, wheel!* in the individual mode (left) and in the collaborative mode (right).

6.3.3 Complex Task: *Prize Claw*

In the individual "*Prize Claw*" task (Figure 6-4), the user is required to perform both grip and movement manipulations. The task is similar to the *Prize Claw Machine* in the real world. The user moves the claw at the top of the machine, then grips to make the claw go down in an attempt to grasp the prize. The user must then move the claw to put the prize into the hole to get rewards. The states of the claw are controlled by the following equations:

$$\begin{gathered} x_{curr} = x_0 + disp_x, \quad if\ y_{last} = y_{top} \\ z_{curr} = z_0 + disp_z, \quad if\ y_{last} = y_{top} \\ des_y = \begin{cases} y_{top}, & if\ C = true \\ y_{middle}, & if\ C = false\ and\ F \in MediumRange \\ y_{bottom}, & if\ C = false\ and\ F \in LargeRange \end{cases} \\ y_{curr} = y_{last} + v_y \times \Delta t, \quad if\ y_{curr} \neq des_y \end{gathered} \tag{6-3}$$

where $disp_x$ and $disp_z$ are the displacements of the user's hand movement along the x and z axis, respectively, x_0, z_0 and y_{top} are the initial positions of the claw, and x_{curr}, y_{curr} and z_{curr} are the new positions of the claw. The des_y is the destination position of the claw along the y axis determined by the applied grip force (F) and the state whether a prize is being caught (C), and v_y is the speed with which the claw moves to the destination position. Greater force makes the claw go deeper to catch the prizes at the bottom, while a smaller force can make the claw catch the prizes at the middle height. When the claw grasps a prize, the claw will take the prize back to the top, and then the user can move it to the hole's location. The user should keep gripping to hold the prize before dropping it. When the user stops gripping, the prize falls into the hole or on the table.

The user is restricted to moving the claw within the prize claw machine. The viscous effect and friction effect accompany the movement of the claw to improve immersion. A resistance force feedback is generated when the claw collides with the glass enclosure of the machine. The user can also feel the change of weight when he/she picks up the prize or drops it into the hole.

In the collaborative mode, game play is portrayed as if two are standing at adjacent sides of the prize claw machine, and control the claw together. They have different game views (e.g., the giraffe is on the right side from the player B's viewpoint, while it is on the left side from the player A's viewpoint in the Figure 6-4) and they can only move the claw side along the plane that corresponds with their viewpoints. To pick up one prize, they must communicate to share the information of the claw position and the prize position on each other's game view, and discuss and work together to position the claw above the same prize according to their respective viewpoints. They must both then grip at the same time to pick the prize up and keep gripping to hold the prize until they release their grippers to drop the prize into the hole. If only one player grips, the claw would not go down to catch the prize. If either one of them releases the gripper before reaching the hole, the caught prize would drop on the table, and they would have to pick up it again. Thus, they should communicate with one another to determine which prize to pick and whether they are ready to pick up and drop off the prize during each manipulation in order to get as many prizes as possible within limited time.

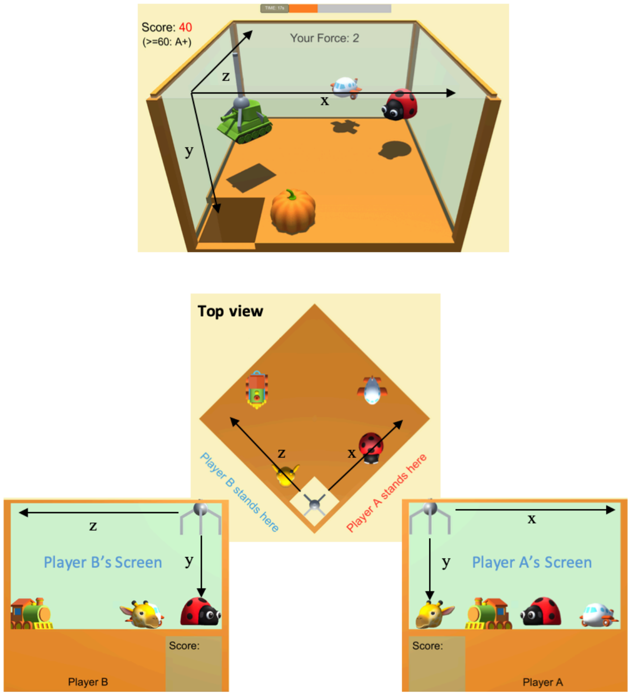

Figure 6-4. The complex task *Prize Claw* in the individual mode (upper) and in the collaborative mode (lower).

6.3.4 Complex Task: *Green Path*

Similar to the "*Prize Claw*" task, the "*Green Path*" task requires both grip and movement manipulations. As shown in Figure 6-5, the user picks up a yellow ball from the upper left corner of a board, and then moves it to the bottom right corner through a "safe" path with the green color. The user can manipulate the size of the ball by adjusting their grip strength. They must change and match the size of the ball with rings that occur along the path in order to win rewards. The states of the ball are controlled by the following equations:

$$\begin{aligned} x_{curr} &= x_0 + disp_x, \quad if\ F > SmallRange \\ z_{curr} &= z_0 + disp_z, \quad if\ F > SmallRange \\ y_{curr} &= \begin{cases} y_{top}, & if\ F > SmallRange\ and\ G = true \\ y_{bottom}, & if\ F \in SmallRange\ and\ G = true \\ y_{last} - at^2, & if\ G = false \end{cases} \\ S_{curr} &= \begin{cases} S_{small}, & if\ F \in LargeRange \\ S_{big}, & if\ F \in MediumRange \end{cases} \end{aligned} \tag{6-4}$$

where y_{top} and y_{bottom} are the y positions of the ball when it is picked up and when it is dropped down on the green path, respectively, a is the falling acceleration when the ball moves outside the green path, G represents if the ball is within the green path, S_{small} and S_{curr} are the ball size when the user grips hard and when the user grips slightly, respectively. Like the *Prize Claw* task, the user can feel the change of weight when the ball is picked up and when it is dropped off.

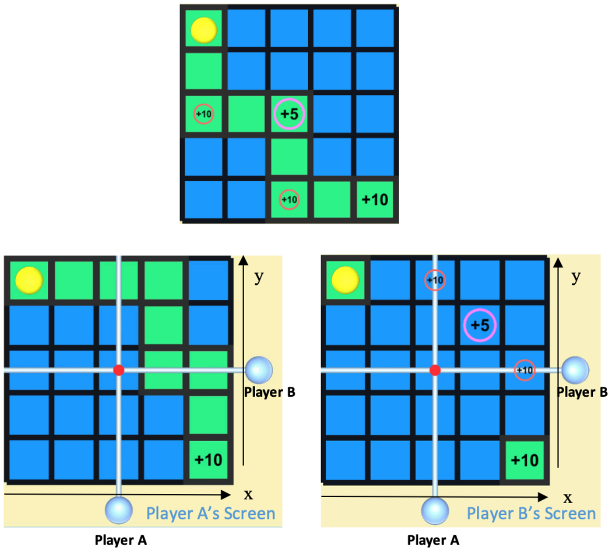

Figure 6-5. The complex task *Green Path* in the individual mode (upper) and in the collaborative mode (lower).

In the collaborative mode, two users work together to move the yellow ball and obtain as many rewards as they can. Each user controls a movement handle. The horizontal handle only moves along the *y* axis, while the vertical handle only moves along the *x* axis. The crossing point (represented by the red dot in Figure 6-5) of the two handles is the control dot that can pick up, move and drop the yellow ball. Only when the control dot is above the yellow ball and both users are gripping can the ball be picked up and moved. Since one user only controls one movement direction of the ball, two users have to work together to move the ball to the destination. To promote the need for communication between users in the collaborative mode, the green path and the reward rings are visible to one user but invisible to the other user. When one user can see the green path, the other one can see the reward rings. Therefore, to be successful, users must share the position information of the green path and the reward rings, and together decide where and when to move the ball or adjust the size of the ball, in order to avoid dropping the ball into the blue areas or missing the rewards on the path.

6.4 Usability Study

We conducted a usability study to (1) assess the usability and the acceptability of C-Hg for children with ASD; to explore (2) whether the system can help improve fine motor task performance in both individual collaborative modes, and (3) how fine motor task performance relate to social skills (communication and collaboration skills).

6.4.1 Participants

In this study, we recruited 10 children with ASD and 10 TD children (ages: 8-12 years, mean age: 10.85 years) through an existing clinical research registry. We then created 10 age- and sex-matched pairs (ASD-TD). Table 6-1 shows the participant characteristics. As seen in Table 6-1**Error! Reference source not found.**, autism symptoms were indexed using the Autism Diagnostic Observation Schedule-Second Edition (ADOS-2) [28], the Social Responsiveness Scale, Second Edition (SRS-2) [29], and the Social Communication Questionnaire – Lifetime score [30]. Detailed participant information can be found in Appendix A.

Table 6-1. Participant Characteristics

Metrics	TD Group (N = 10) M(SD)	ASD Group (N = 10) M(SD)
Age (Years)	10.85 (1.86)	10.94(1.36)
SRS-2 total raw score	23.5(25.61)	103.25(21.76)
SRS-2 T-score	48.6(15.05)	79(8.14)
SCQ Lifetime total score	2.5(2.59)	21.75(7.38)

ADOS-2 total score	/	17.88(3.97)

6.4.2 Procedure

Each participant pair came three times approximately one week apart (Figure 6-6). Each participant pair were required to complete a pre-test and an individual training session in their first visit, two individual training sessions in their second visit, and an individual training session and a post-test in their third visit.

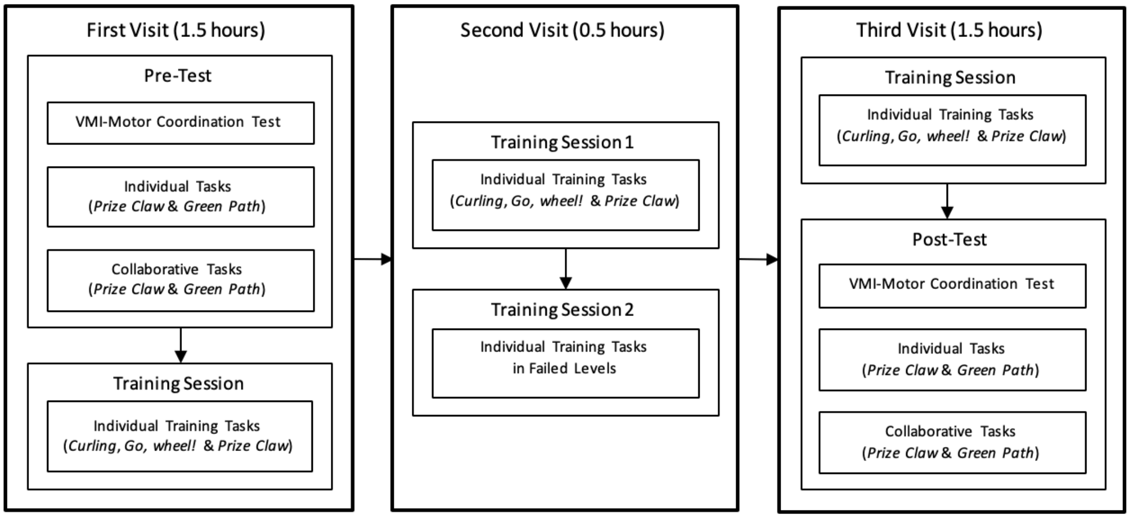

Figure 6-6. The Study Procedure.

The pre- and post-tests in their first visit and third visit consisted of a mix of virtual and real-world tasks. To measure fine motor performance in real-world tasks, we used the Motor Coordination subtest of the Beery-Buktenica Developmental Test of Visual-Motor Integration (VMI Motor Coordination Test) [31]. The four individual virtual tasks (two *Prize Claw* and two *Green Path*) and four collaborative tasks (two *Prize Claw* and two *Green Path*) were designed to assess the within system fine motor skills (hand movement and grip control skills) that were practiced in the individual training sessions as well as the social skills (communication and collaboration skills) that were required in the collaborative tasks.

In the individual training sessions, each participant completed a grip task (*Curling*), a movement task (*Go, wheel!*) and a complex task (*Prize Claw*). These tasks were developed in three levels of difficulty and the system would adaptively adjust the difficulty level for each task according to the participant's real-time performance (Table 6-2). The participants started from the easiest level (Level 1). If they could achieve the goal within the given task time (1 minute), they would be allowed to enter the next harder level. Otherwise, they would have to go back to the lower level or stay at the lowest level (Level 1) to take more practices. Each task was ended when the participant achieved the goal in Level 3 or after the participant finished five trials. For the *Curling* task, the task level was developed by decreasing the size of the circular target to increase the task difficulty. For the *Go, wheel!* task, the golden coins move with the same speed in Level 1 and with varying speeds in Level 2. In Level 3, some rocks appear on the road that the participant needs to avoid rocks in order to maintain higher scores. For the *Prize Claw* task, all the prizes are randomly placed on the table and the participant needs to apply greater force to grab them in Level 1. In Level 2, some prizes stay in the air and the participant needs to apply slight grip force to catch them. In Level 3, all the prizes are moving on the table and the participant needs to carefully consider where and when to put down the claw in order to catch the moving prizes.

Table 6-2. Training Task Configurations.

Tasks	**Level 1**	**Level 2**	**Level 3**
Curling	Large target	Medium target	Small Target
Go, wheel!	Constant target speed	Varying target speed	Varying target speed, Rock obstacles
Prize Claw	All targets stay on the table	Some targets stay in the air	All targets move on the table

As shown in Figure 6-6, each participant only took one training session after the pre-test in the first visit, and one training session before the post-test in the last visit. However, in order to provide more practice opportunities, each participant was required to take two training sessions (Training Session 1 and Training Session 2) in the second visit. Training Session 1 was same as the training sessions provided in the first visit and second visit, which provided the training tasks in the adaptive way as described in the previous paragraph. Each participant first completed Training Session 1, and at the same time, the system recorded the failed level of the participant in each task, which was the most difficult level for the participant to complete. Then, in Training Session 2, each participant only took the tasks in the failed level. For example, if one participant successfully completed Level 1 of *Curing* Task, but failed to complete Level 2, Level 2 was the failed level of *Curing* Task for this participant. Thus, in Training Session 2, the participant only took the *Curing* Task in Level 2 that was challenging for the participant.

6.5 Results and Discussions

Participants provided feedback about their experiences using the system by completing a paper-and-pencil questionnaire at the end of their third visit. Due to the small sample size, we used the Wilcoxon signed-rank test to compare participant pre- and post-test performance [32]. We also reported r effect sizes with the significance cutoffs of large (>0.5), medium(>0.3) and small (>0.1) [33].

6.5.1 Acceptability of the C-Hg System

We collected participant feedback about the Haptic Gripper and virtual games with a 5 point-Likert scale questionnaire including nine questions. Table 6-3 shows the survey questions as well as the participants' responses.

Table 6-3. The Survey Feedback of TD Group (N = 10) and ASD group (N = 10)

No.	**Questions**	**TD M(SD)**	**ASD M(SD)**	***t (18)***	***p***
1	How difficult was it to use the Haptic Gripper? (5-very difficult, 1-very easy)	2.5(0.97)	2.5(0.97)	0.0	1.0
2	How much did you like to use the Haptic Gripper to play games? (5-very much, 1-not at all)	3.8(1.03)	3.3(1.42)	0.90	.379
3	How much did you like these haptic effects? (5-very much, 1-not at all)	3.9(0.88)	3(1.15)	1.96	.065
4	How useful are these haptic effects to help you understand your operations? (5-very useful, 1-absolutely useless)	3.4(0.97)	3.3(1.49)	0.12	.909
5	How did you do to manipulate the Haptic Gripper? (5-excellent, 1-very bad)	3.8(0.95)	3.4(1.07)	0.95	.355
6	How much did you like these games? (5-very much, 1-not at all)	4(1.25)	3.8(1.14)	0.38	.712
7	How difficult was it to understand how to play these games? (5-very difficult, 1-very easy)	1.9(0.99)	2.2(1.14)	-0.6	.538
8	How important was it to talk to your partner in order to win the collaborative games? (5-very important, 1- absolutely useless)	4.4(0.70)	4.1(1.20)	0.68	.503
9	How important was it to work together with your partner in order to win the collaborative games? (5-very important, 1- absolutely useless)	4.3(1.25)	4.3(0.95)	0.0	1.0

The responses to questions 1-5 indicated that the interactive Haptic Gripper device was well accepted by the participants. It was not difficult for participants to learn how to use the Haptic Gripper and to perform manipulations through it in the game. Most of them expressed interest in using this device with haptic effects to play video games. They also reported that the haptic effects were useful to help them understand their manipulations. The responses to questions 6-7 indicated that the virtual games were easy to understand and the participants enjoyed these games. The responses to questions 8-9 indicated that the virtual games could promote communication and collaboration between partners. All these results suggested that C-Hg system was well designed to maintain the participant's interests on the virtual tasks as well as to provide social interaction opportunities. The *t*-tests did not reveal significant differences in mean responses across groups (all *p* values > .05).

6.5.2 Performance Improvement

Table 6-4 presents the performance results of both the TD group and the ASD group in the individual fine motor skill training tasks. Both groups achieved statistically significant improvements on the VMI Motor Coordination test (*VMI*) with large/medium effect sizes (TD: *Relative Change* (*RC*) = 6.57%, $Z = -2.26$, $p = .024$, $r = -.51$; ASD: *RC* = 15.38%, $Z = -2.21$, $p = .027$, $r = -.49$). According to the VMI standard score interpretation [31], the performance of the TD group remained at the average level (90-109) in both pre-test (99) and post-test (105.5), while the ASD group was at the below-average level (80-89) in the pre-test (84.5) and reached the average level in the post-test (97.5). As for the individual virtual fine motor tasks, both groups showed statistically significant improvements with large effect sizes (TD in **Ind**ividual ***P**rize* ***C**law* tasks: *RC* = 22.2%, $Z = -2.67$, $p = .008$, $r = -.60$; ASD in **Ind**ividual ***P**rize* ***C**law* tasks: *RC* = 61.5%, $Z = -2.69$, $p = .007$, $r = -.60$; TD in **Ind**ividual ***G**reen* ***P**ath* tasks: *RC* = 44.3%, $Z = -2.80$, $p = .005$, $r = -.63$; ASD in **Ind**ividual ***G**reen* ***P**ath* tasks: *RC* = 26.1%, $Z = -2.71$, $p = .007$, $r = -.61$). These results suggested that the individual fine motor skill training tasks had a positive impact on participant fine motor skills.

Table 6-4. Individual Performance Results

Metrics	**TD Group (N = 10)**						**ASD Group (N = 10)**					
	Pre Mdn	**Post Mdn**	***RC* (%)**	***Z***	***p***	$\lvert r \rvert$	**Pre Mdn**	**Post Mdn**	***RC* (%)**	***Z***	***p***	***r***
VMI	99	105.5	6.57	-2.26	$.024^*$	$-.51^\dagger$	84.5	97.5	15.4	-2.21	$.027^*$	-.49
Ind PC	4.5	5.5	22.2	-2.67	$.008^*$	$-.60^\dagger$	3.25	5.25	61.5	-2.69	$.007^*$	$-.60^\dagger$
Ind GP	22	31.75	44.3	-2.80	$.005^*$	$-.63^\dagger$	22	27.75	26.1	-2.71	$.007^*$	$-.61^\dagger$

VMI, scores on the VMI Motor Coordination test

Ind PC, individual *Prize Claw* task score

Ind GP, individual *Green Path* task score

*RC, relative change computed by (post - pre)/pre *100%*

$^*p<.05$, $^\dagger|r|>0.5$

6.5.3 Impact of Fine Motor Skill Training on Social Skills

The collaborative performance results are shown in Table 6-5. We found statistically significant improvements of both groups regarding the task score in the collaborative tasks (***Col**laborative* ***P**rize* ***C**law* tasks: *RC* = 9.5%, $Z = -2.55$, $p = .011$, $r = -.57$; ***Col**laborative* ***G**reen* ***P**ath* tasks: *RC* = 16.75%, $Z = -2.8$, $p = .005$, $r = -.63$). The Spearman's rank correlation analysis also found strong/medium correlations between the performance results of individual tasks and collaborative tasks (ASD in ***P**rize* ***C**law* tasks: $\rho = 0.498$, $p = .025$; TD in ***P**rize* ***C**law* tasks: $\rho = 0.208$, $p = .379$; ASD in ***G**reen* ***P**ath* tasks: $\rho = 0.427$, $p = .061$; TD in ***G**reen* ***P**ath* tasks: $\rho = 0.574$, $p = .008$), which indicated that the improvements in collaborative tasks were related to improvements in individual tasks. These results might suggest that through practicing fine motor skills in the individual training tasks, participants were more likely to perform better in collaborative fine motor tasks, which required communication and collaborative operations.

Table 6-5. Collaborative Performance Results of TD-ASD Pairs (N = 20, Pairs = 10)

Metrics	**Pre**	**Post**	***RC***	***Z***	***p***	***r***
	Mdn	Mdn	***(%)***			
Col PC	9.5	12.75	34.2	-2.55	$.011^{*}$	$-.57^{\dagger}$
Col GP	16.75	31	85.0	-2.80	$.005^{*}$	$-.63^{\dagger}$
ASD PC Col Ratio	0.49	0.63	26.6	-2.40	$.017^{*}$	$-.54^{\dagger}$
TD PC Col Ratio	0.57	0.65	13.2	-1.58	.114	-.35
ASD GP Col Ratio	0.75	0.81	7.85	-1.99	$.047^{*}$	-.44
TD GP Col Ratio	0.77	0.81	4.94	-1.27	.203	-.29
ASD Col PC INIT	12	15.25	27.1	-0.77	.44	-.17
TD Col PC INIT	20.75	15.25	-26.5	1.27	.20	.28
ASD Col PC RESP	10	6	-.4	0.49	.62	.11
TD Col PC RESP	8.47	7	-.2	0.35	.72	.08
PC Col INIT Switch	15.25	16.25	6.56	0.49	.62	.11
ASD Col GP INIT	13.25	18.75	41.5	-2.14	$.033^{*}$	-.48
TD Col GP INIT	17.75	18.5	4.23	-1.48	.139	-.33
ASD Col GP RESP	5.75	5.5	-4.35	0.41	.682	.09
TD Col GP RESP	5.75	4.75	-17.4	1.07	.282	.24
GP Col INIT Switch	14.5	17	17.2	-1.89	.059	-.42

Col PC, collaborative *Prize Claw* task score

Col GP, collaborative *Green Path* task score

Col Ratio, the ratio of collaborative operations to total operations

INIT, the frequency of initiating a conversation

RESP, the response frequency

INIT Switch, the switch frequency of conversation initiator

*RC, relative change computed by (post - pre)/pre *100%*

$^{*}p<.05$, $^{\dagger}|r|>0.5$

We also found that all participants, whether with ASD or TD performed much more collaborative manipulations in the collaborative tasks of the post-test. Specifically, participants with ASD significantly increased their collaborative manipulations in the collaborative tasks of post-test (***Col**laborative* ***Ratio*** of *ASD* in *collaborative* ***P**rize* ***C**law* tasks: *RC* = 26.6%, *Z* = -2.4, *p* = .017, *r* = -.54; ***Col**laborative* ***Ratio*** of *ASD* in *collaborative* ***G**reen* ***P**ath* tasks: *RC* = 7.85%, *Z* = -1.99, *p* = .047, *r* = -.44). These results indicated increased interaction and collaboration between partners in the collaborative tasks of post-test, and might suggest that improved fine motor skills would promote collaborative activities of participants.

To analyze the conversation pattern of participants, two human coders (trained graduate students with experience collecting and analyzing qualitative and quantitative data) were recruited to manually transcribed and coded the conversation audios from 80 recorded videos of collaborative tasks (four hours of video data in total). We provided a framework that described the concrete definitions of types of utterances, and a few examples about how to code the conversation data for the human coders. Each human coder independently coded the same data. After each rater completed coding, a percent agreement of 92.5% was found. For the codes that were not in agreement, the human coders reconciled differences via a consensus in which any discrepancies were discussed and resolved.

As described in Section 6.3, the conversations between two players in all the collaborative tasks involved strategy discussion and information sharing. Timely communication was important for players to obtain higher scores. In order to evaluate how often one player communicated with his/her partner, we defined three types of utterances, *Initiation* (*INIT*), *Response* (*RESP*), and *Initiation Switch* (*INIT Switch*). *Initiation* represented one player's statement that started a conversation. *Response* represented one player's feedback to the partner's statement. *Initiation Switch* represented the switch of the conversation initiator from one player to the other one. Based on the final coding data, we calculated the frequency of *INIT*, *RESP*, and *INIT Switch* in each collaborative task. Table 6-6 shows a sample of three conversations recorded in a collaborative *Green Path* task. First, Player A started a conversation asking where to go, and Player B responded with the direction information (recall that path position was only visible to one player). Second, Player B started a new conversation to direct the movement. Then, Player A started another conversation to provide the reward information (recall that reward position was only visible to one player), and Player B responded with an acknowledgement. Therefore, there were two *INITs* of Player A, one *INITs* of Player B, and two *RESPs* of Player B. We also see that the conversation initiator switched from Player A to Player B, and then switched back to Player A. Thus, we counted the frequency of *INIT Switch* as 2.

Table 6-6. A sample of conversations recorded in a collaborative *Green Path* task.

No.	**Player A**	**Player B**
1	Now where will we go? <*Initiation*>	Left. <*Response*>
2		Right. Down. Right, right. <*Initiation*>
3	Wait, right here. There is a reward. <*Initiation*>	Okay. <*Response*>

As shown in Table 6-7, the results indicated that in all the collaborative tasks of the pre-test and post-test, both the ASD and TD participants initiated more conversations than providing responses, which is reasonable since participants could respond to his/her partner with an action instead of an utterance. However, we found that the TD participants maintained a significant difference between initiations and responses, no matter in the pre-test or in the post-rest (**TD** in ***Col***_laborative_ ***P***_rize_ ***C***_law_ tasks of ***Pre***-test: $Z = 2.81$, $p = .005$, $r = -.63$; **TD** in ***Col***_laborative_ ***P***_rize_ ***C***_law_ tasks of ***Post***-test: $Z = 2.66$, $p = .008$, $r = -.59$; **TD** in ***Col***_laborative_ ***G***_reen_ ***P***_ath_ tasks of ***Pre***-test: $Z = 2.70$, $p = .007$, $r = -.60$; **TD** in ***Col***_laborative_ ***G***_reen_ ***P***_ath_ tasks of ***Post***-test: $Z = 2.80$, $p = .005$, $r = -.63$), while the difference among ASD participants is only significant in the post-test (**ASD** in ***Col***_laborative_ ***G***_reen_ ***P***_ath_ tasks of ***Post***-test: $Z = 2.30$, $p = .021$, $r = -.51$; **ASD** in ***Col***_laborative_ ***G***_reen_ ***P***_ath_ tasks of ***Post***-test: $Z = 2.80$, $p = .005$, $r = -.63$). The results showed in Table 6-5 also indicated that ASD participants made more initiations in the post-test, and the significant improvements were found in the ***Col***_laborative_ ***G***_reen_ ***P***_ath_ tasks ($Z = -2.14$, $p = .033$, $r = -.48$). These results might suggest increased active communication among the ASD participants, and they tended to provide information or commands in the post-test. In addition, in the post-test, the switch frequency of who initiated a conversation increased (***INIT Switch*** in _collaborative_ ***P***_rize_ ***C***_law_ tasks: $RC = 6.56\%$, $Z = 0.49$, $p = .62$, $r = -.11$; ***INIT Switch*** in _collaborative_ ***G***_reen_ ***P***_ath_ tasks: $RC = 17.2\%$, $Z = -1.89$, $p = .059$, $r = -.42$), though no significant difference was found, which also suggested that participants more actively and effectively communicated with their partners to share information or provide commands in the post-test collaborative tasks. Considering the improvements in task performance, these results might suggest that having the opportunity to practice fine motor skills could foster more active communication.

Table 6-7. The comparison between initiation frequency and response frequency among the ASD group (N = 10) and TD group (N = 10)

Metrics	***INIT***	***RESP***	***Z***	***p***	***r***
	Mdn	Mdn			
ASD Col PC PRE	12	10	1.74	.082	.39
TD Col PC PRE	20.75	8.47	2.81	.005*	.63†
ASD Col PC POST	15.25	6	2.30	.021*	.51†
TD Col PC POST	15.25	7	2.66	.008*	.59†
ASD Col GP PRE	13.25	5.75	1.38	.169	.31
TD Col GP PRE	17.75	5.75	2.70	.007*	.60†
ASD Col GP POST	18.75	5.5	2.80	.005*	.63†
TD Col GP POST	18.5	4.75	2.80	.005*	.63†

Col PC, collaborative *Prize Claw* task score

Col GP, collaborative *Green Path* task score

INIT, the frequency of initiating a conversation

RESP, the response frequency

$^*p<.05$, $^\dagger|r|>0.5$

6.6 Conclusion and Future Work

Many individuals with ASD have not only social-communication challenges, but also delays in their fine motor skills. Because fine motor performance is inherent to many social-communication tasks of childhood, such as playing a board game or completing a group assignment, these fine motor deficits may impact their ability to engage with real-world social activities. To provide opportunities for fine motor skill practice within an automated measurement system and collaborative peer context, we developed a collaborative haptic-gripper skill training system (C-Hg). By using a customized Haptic Gripper, the system is able to provide the grip control training and hand movement training in both individual mode and collaborative mode. In the individual mode, the system can adaptively adjust the difficulty level of fine motor skill training tasks according to the user's real-time performance. In the collaborative mode, the user is required to communicate and collaborate with the partner to complete the collaborative fine motor skill training tasks together. These tasks simultaneously engage fine motor as well as social-collaboration skills in children with ASD while allowing us to investigate how they relate to each other.

This usability study with 10 children with ASD and 10 TD children indicated that this system was well accepted by all participants, regardless of diagnostic status. Both ASD children and TD children showed significant improvements on the VMI pre- and post-test, reflecting the relevance of the task to standardized real-world motor assessment tools. Participants in both groups also showed significant improvements in performance during individual and collaborative tasks, which suggests that this system not only impacts individual fine motor skills, but also fosters social communication and collaboration. We also found strong/medium correlations between individual task performance and collaborative task performance, indicating that improved individual fine motor skills relate to better performance in social collaborative tasks. In addition, participants with ASD were found to conduct more collaborative manipulations and initiate more conversations with their partners in the post-test, suggesting that more active collaboration and communication of participants with ASD happened after practicing in the individual fine motor tasks. These results demonstrated that fine motor skill practice might have positive impacts on communication and collaboration skills of participants with ASD in the collaborative tasks.

Our findings underscore that social and communication skills do not occur in isolation; they relate not only to each other, but also to the complexity of the world around us. For people with ASD and challenges with fine motor skills, many important, everyday social tasks with motor components (such as playing a game) could be doubly affected, by ASD as well as these motor challenges, with the added difficulty across both domains straining EF skills and impacting performance. Motor skills are a common target of standardized intervention and assessment across the lifespan. For example, young children with ASD and fine motor delays often receive occupational therapy services embedded in their classroom special education supports [34, 35]. For older adolescents, emerging research supports the use of tasks such as collaborative Lego building [36, 37] for assessment of work relevant skills. If combined social and motor demands place increased strain on already stressed EF skills for individuals with ASD, a multicomponent approach to assessment and intervention may benefit many people.

Our system, to our knowledge, is the first to explore the influence of movement and grip control skills on the social communication and interaction skills of children with ASD through virtual environments. We provided collaborative fine motor tasks that requires multitasking of participants to plan and coordinate their manipulations and communications. Additionally, our tasks provided haptic input which may make them more inherently rewarding and engaging. Our results suggested that improved collaborative task performance and increased active communication and collaboration were related to improved individual fine motor task performances. This supports the findings of MacDonald [18] who reported that children with weaker motor skills have greater social communicative skill deficits, and Srinivasan et al. [23] who suggested socially embedded movement-based contexts are valuable in promoting imitation/praxis, interpersonal synchrony and motor performance. Our activities hold potential for supporting, intervening on, and measuring multiple skills important for social success, paving the way for automated systems that minimize the need for intensive therapist oversight.

Though the presented work is promising, the results should be interpreted within the context of several limitations. First, the relatively small sample size and short intervention duration of the study, and the absence of a control group undermine the generalizability of the results. Future studies will include more participants, training sessions and matched control groups. Second, though fine motor skills were shown to positively affect social interaction performance, more specific metrics should be developed to explore how they map to each other as well as EF domains. In addition, the human-to-human collaborative mode in the current system requires two users to align their availability. A stand-by partner (e.g., a virtual agent) would be preferable to perform the collaborative training at any time. This kind of agent system would also be helpful to reduce the burden for manually analyzing the communication data. Therefore, we will integrate a human-to-agent collaborative mode in C-Hg system in the future work. Despite these limitations, the C-Hg system is one of the first computer-assisted system that enable simultaneously fine motor skill training and social skill training for children with ASD. The encouraging results provide important preliminary insights into developing more comprehensive multi-skill training environments.

Appendices

A. The participant information

Table 6-8. Detailed Information of Participants

ID	**Age**	**IQ**	**SRS-2 total raw score**	**SRS-2 T-score**	**SCQ Lifetime total score**	**ADOS-2 total score**
ASD1	10.77	105	119	84	18	17
TD1	9.30	/	21	45	8	/
ASD2	11.79	93	130	90	25	19
TD2	12.99	/	11	42	0	/
ASD3	12.77	84	110	80	29	22
TD3	12.71	/	41	53	1	/
ASD4	12.14	49	90	72	18	24
TD4	12.49	/	90	90	4	/
ASD5	11.17	100	105	82	28	18
TD5	11.36	/	15	44	1	/
ASD6	11.21	98	100	76	31	13
TD6	11.98	/	14	42	0	/
ASD7	9.26	101	106	82	17	17
TD7	8.97	/	7	41	3	/
ASD8	11.43	114	66	66	8	13
TD8	11.72	/	2	39	0	/
ASD9	10.66	/	89	75	15	/
TD9	9.13	/	13	43	4	/
ASD10	8.15	90	61	64	16	13
TD10	7.81	/	21	47	4	/

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CHAPTER 7

INC-Hg: AN INTELLIGENT COLLABORATIVE HAPTIC-GRIPPER VIRTUAL REALITY SYSTEM

7.1 Abstract

In the last chapter, we described the development of a Collaborative Haptic-gripper Virtual Reality system (C-Hg) that can support human-to-human communication and interaction through collaborative fine motor tasks. This system showed potential to enhance flexible and spontaneous communication as well as within-system haptic interaction between the users. However, it also required appropriate age-matched partners to be available at the same time to promote interaction. Inappropriate partners (such as those of a different age group or developmental level) might reduce the user's engagement with the system and thereby impact training outcomes. A second shortcoming of these more naturalistic peer-based designs is the intensive resources required to manually code the unrestricted conversations that occurred during the peer-based interactions.

In order to preserve the benefits of CVE-based platforms and mitigate some of the disadvantages related to peer availability and resource limitations, we developed an Intelligent Collaborative Haptic-Gripper VR System (INC-Hg). This system provides an intelligent agent who can understand, communicate and haptically interact with the user, without requiring the presence of another human peer. The INC-Hg operates in real time, and thus is able to perform collaborative training tasks at any time and at the user's pace. INC-Hg can also record real-time data regarding spoken language and task performance, thereby greatly reducing the resource burden of communication and interaction performance analysis.

To evaluate INC-Hg, specifically system acceptability and agent functionality, we conducted a preliminary usability study with 10 participants with ASD (age: 8-12 years). Participants with ASD reported that they liked to perform the collaborative tasks with the agent and enjoyed the haptic interaction with the agent, supporting system usability and tolerability within this population. Results also indicated that the system could classify the participant's utterances into five classes with the accuracy of 70.34%, which suggested the potential of INC-Hg to automatically recognize and analyze conversational content. The results also indicated high accuracies of the agent to initiate a conversation (97.56%) and respond to the participants (86.52%), suggesting the capability of the agent to conduct proper conversations with the participants. Compared to the results of human-to-human collaborative tasks, the human-to-agent mode achieved higher average collaborative operation ratio (61% compared to 40%), and comparable average

frequencies for *Initiations* and *Responses* among the participants with ASD, which offered the preliminary support as well as areas of improvement regarding the agent's ability to respond to participants, work with participants to complete tasks, and engage in back-and-forth conversations, and suggested the potential of the agent to be a useful partner for individuals with ASD completing CVE tasks.

7.2 Introduction

In Chapter 2 and Chapter 6, we discussed the advantages of Collaborative Haptic Virtual Environments (CHVEs) as social interaction platforms to support flexible communication and interaction of multiple online users. The CVE-based skill training systems have shown the potential to improve the learning outcomes of children with ASD through social interaction with their peers in the collaborative tasks [1-3]. However, these systems are limited to providing intensive one-to-one ASD interventions due to unavailability of partners or interacting with inappropriate partners. In order to perform well in the collaborative skill training tasks in the CVE system, children with ASD require appropriate peer partners (e.g., partners with same age or developmental level; able to complete tasks) to be present online at the same time. In addition, although these systems are able to record spoken language, they do not conduct efficient verbal communication analyses. Since users are allowed to carry on unrestricted conversations as part of promoting naturalistic interactions, manually analyzing the recorded conversation data is a time-consuming and resource-intensive task. To address these limitations, we proposed an adaptive CVE-based skill training system that is able to provide an appropriate partner for any user, as well as perform real-time autonomous verbal communication analysis.

Creating an AI-agent with the capability of automatically perceiving the user's behaviors and appropriately responding to the user with the human-style intelligence is one solution to implement this kind of adaptive CVE system [4]. A few studies have attempted to design intelligent tutors to help children with ASD practice communication skill and language skill [5, 6]. However, most existing intelligent agent systems have limited autonomy. Such agents are either pre-programmed with limited responses or controlled using the "Wizard of Oz" methodology. Therefore, one goal of our work is to develop a conversational agent that can conduct flexible and spontaneous domain-specific conversations with the user in the collaborative tasks. In addition, few existing agents are able to interact with the user haptically in addition to converse with the user. Social interactions often involve activities that require proficient motor skills to participate with success [7]. Focusing on designing training activities that targets only one specific skill of children with ASD may hinder the applications of the learnt skills in the complex real-world activities. Haptics provides a feeling of realism in virtual interaction [8]. With haptic devices, users are able to feel the effect of their manipulations and interactions with the virtual environment in the form of force feedback. Therefore, we wanted to develop a training system that allows users to practice social communication and collaboration skills as well as fine motor skills (hand movement and grip control skills) during the collaborative haptic tasks.

In this chapter, we introduced an Intelligent Collaborative Haptic-Gripper System (INC-Hg) that provides an agent to perform a collaborative fine motor task (*Prize Claw*) with the user. The agent is able to (1) automatically recognize the user's speech and action, and extract specific domain-related communication data for analysis, (2) appropriately respond to the user verbally and/or haptically, (3) spontaneously initiate a conversation and/or an haptic interaction, and (4) repeatedly perform the tasks with different users and conduct consistent performance evaluations. We conducted a usability study with 10 children with ASD to investigate the acceptability of the agent among the children with ASD as well as the system functionality. The results demonstrated the capability of the agent as a virtual partner to communicate and interact with the user, and the capability of the system to automatically measure the communication and interaction performance of the user.

The rest of the chapter is organized as follows. Section 7.3 discusses the related work on the investigation of existing agent systems and spoken dialogue technology for implementing the agent system. Section 7.4 presents the system design, which is followed by the usability study in Section 7.5. The results and discussions of the study are presented in Section 7.6. Finally, we summarize the contributions of the work and discuss its limitations in Section 7.7.

7.3 Related Work

7.3.1 Agent Systems for Autism

A few studies have used intelligent agent systems to address the language skills [6], and social interaction skill [5, 9, 10] of children with ASD. However, most intelligent agents are designed with little autonomy, which still leads to great resource demand. For example, Mower et al. [11] utilized a virtual conversational agent, Rachel, as an emotional coach to interact with children with ASD in a set of emotion problem-solving tasks. Rachel was designed using the Wizard of Oz (WoZ) paradigm, and was remotely controlled by a wizard using a control panel to select an action from a limited set of pre-defined available actions. Their pilot study with two children with ASD suggested that Rachel was an effective tool to elicit social conversational behaviors of children with ASD. Tartaro et al. [12] developed a virtual peer, Sam, to perform a collaborative narrative task with children with ASD, aiming to facilitate contingent discourse among children with ASD. Sam is a life-sized, animated child, and could use pre-recorded speech and scripted gestures during the storytelling. They compared the interaction of children with ASD with their peers to those with virtual peers, and found that aspects of contingency are more likely to occur with virtual peers, and more likely to increase over time with virtual peers. However, both of these studies either required a human to control the agent or sacrificed spontaneous communication to promote agent autonomy.

Only a few studies have attempted to develop fully autonomous agents [13, 14]. For example, Milne et al. [9] developed a conversational social tutor, Thinking Head, for teaching facial recognition and social situational understanding skills to children with ASD. Thinking Head could generate appropriate speech and realistic facial expressions according to the user's inputs (e.g., clicking choice buttons and typing texts) on the interface. Their experiments with 14 children with ASD demonstrated significant overall performance improvements of participants in the post-test and positive feedback of the system used for social skill education from participants and their caregivers. However, users were not allowed to engage in a spoken conversation with the Thinking Head, which put limits on the generalizability of learnt skills in actual social interactions. Bernardini et al. [5] developed an intelligent game, ECHOES, for fostering social communication in children with ASD. The system included a virtual agent who can interact with the user verbally using simple language (e.g., "My turn!" and "Good job!") and/or non-verbally through gaze and gestures (e.g., pointing at an object) and act autonomously. In a study of 29 children with ASD, results suggested that children with ASD used the agent, but did not find significant transfer of social communication skills.

7.3.2 Haptic Agent Systems

Though fully autonomous agent systems have recently attracted more attention in the field of ASD research, most autonomous agents focus on teaching children with ASD specific skills (e.g., teaching appropriate responses to a predefined set of social situations) rather than on providing spontaneous social interaction experiences. In addition, to our knowledge, no intelligent agent exists that allows children with ASD to converse as well as to engage in haptic interactions with the agent. Agents with haptic feedback have been explored in emotion expression recognition [15], skill training and coaching [16] and social interaction [17]. For example, Huisman et al. [17] developed an embodied conversational agent that could touch the user's forearm. The user, wearing a vibrotactile display, could view his/her forearm through a tablet running an augmented reality (AR) application. More generally, haptic agents have recently gained much attention in the field of physical human-robot interaction (pHRI). Several haptic agents have been developed as assistive devices in industrial applications [18-20]. For example, Yokoyama et al. [21] developed a biped humanoid robot HRP-2P that can carry an object cooperatively with a human based on the voice commands by the human. However, most existing haptic agents can only accept commands from humans or perform independent tasks, with few interactions with humans. A very limited number of research works have contributed to the implementation of interaction beyond simple and passive cooperation, by introducing role switching and continuously adapting interaction [22-24].

7.3.3 Spoken Dialogue Systems

Ideally, an interactive agent will be able to conduct accurate and fluent conversations with the user. To design the conversational behaviors of an intelligent agent, one can utilize spoken dialogue systems, which can “understand” spoken language and enable systems to converse with a human. Though current technologies are not able to create a spoken dialogue system to conduct unrestricted naturalistic conversations, it is feasible to develop a domain-specific spoken dialogue system with constrained grammars and rules with respect to the task specifications. These kind of spoken dialogue systems have been developed in a wide range of fields, such as education, travel, computer games, research and commercial applications [25-28].

Because the goal of our work is to develop an agent that could not only communicate with the user but also interact with the user in the collaborative tasks, we explored previous applications of dialogue systems in collaborative games. Usually, spoken dialogue systems are used to develop Non-Player Characters (NPCs), or game-based characters that can conduct a limited set of pre-defined conversations or commands with the player [29-32]. Only a few spoken dialogue systems have been developed to support flexible conversations within the collaborative game domain [31, 33, 34]. For example, Cuayahuitl et al. [33] developed an intelligent agent with strategic conversational skills for the board game of Settlers of Catan. In the board game, players (the human and the agent) can offer resources to other players and they can also reply to offers made by other players. Cuayahuitl et al. used deep reinforcement learning (DRL) method to train the agent’s conversational skills, and observed that the DRL significantly outperformed several other methods, including random, rule-based, and supervised methods. Fraser et al. [31] used the Alana conversational AI [35] to develop a conversational agent system allowing unrestricted user speech input when talking to NPCs. They also used emotion detection and emotional dialogue management to enhance the conversational experience. To get the information needed in the game, the player is required to talk with the NPCs and manipulate the NPCs’ emotional states by being very polite or rude. Preliminary findings suggested that a spoken conversational interface with emotional dialogue capability is more engaging for the player.

7.4 INC-Hg System Design

In the INC-Hg system, an intelligent agent was developed as a virtual partner to communicate and interact with the user while performing collaborative object-manipulation tasks. To complete the collaborative tasks, the user and the agent must work together. There are no a priori role distributions (e.g., one is assigned as a leader and the other is assigned as a follower), but rather, role distributions emerge organically depending on the interaction history [22]. Like a human, an effective agent should be equipped with the ability to recognize the user’s speech and actions (e.g., haptic information related to direction and force) and the states of the virtual tasks (e.g., the position and status of the target), with the processing capability to analyze the perceived information and make decisions, and with actuators to affect the user and the virtual environment with appropriate actions.

Figure 7-1 shows a simplified INC-Hg system architecture with three major modules to implement the agent functionality. The user and the agent can interact with each other as well as interact with the objects in the virtual environment. The *Collaborative Haptic Virtual Environment (CHVE) Module* manages the states of virtual tasks and generates the combined feedback (visual, auditory and haptic feedback) to the user according to the behaviors of the user and the agent. The *Agent Module* monitors the user's speech and actions as well as the state of CHVE, and generates appropriate actions on the user and/or the CHVE accordingly.

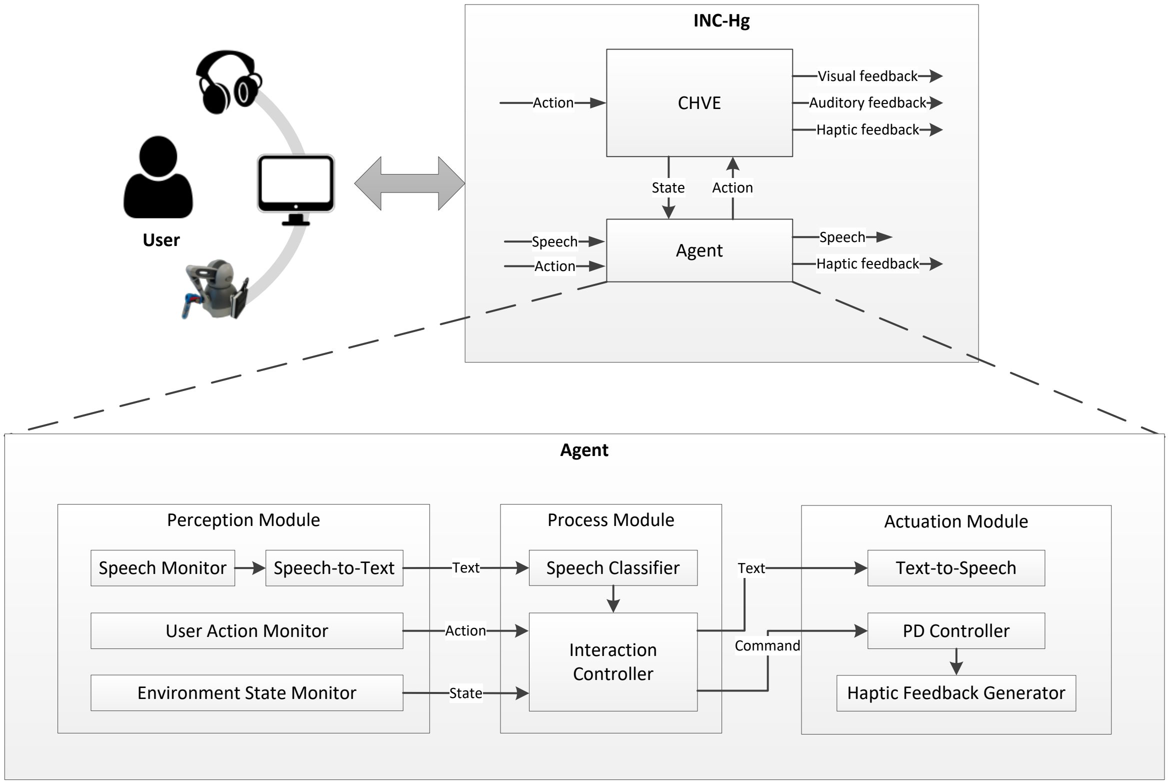


Figure 7-1. The INC-Hg system architecture.

7.4.1 Collaborative Haptic Virtual Environment (CHVE)

The Collaborative Haptic Virtual Environment (CHVE) allows users to engage in haptic interactions with their partners. In Chapter 4, we developed a customized haptic interactive tool, Haptic Gripper, for the user to perform fine motor tasks (Figure 7-2). The Haptic Gripper was constructed by augmenting a commercial haptic device, the Geomagic Touch Haptic Device [36], with a 3D-printed gripper embedded with force sensing resistors (FSRs). With the Haptic Gripper, the user can manipulate (such as moving and gripping) the virtual objects in the virtual space. In addition, the user can feel the existence of the virtual objects and feel the manipulations of the partner, which may foster a more realistic sense of cooperation.

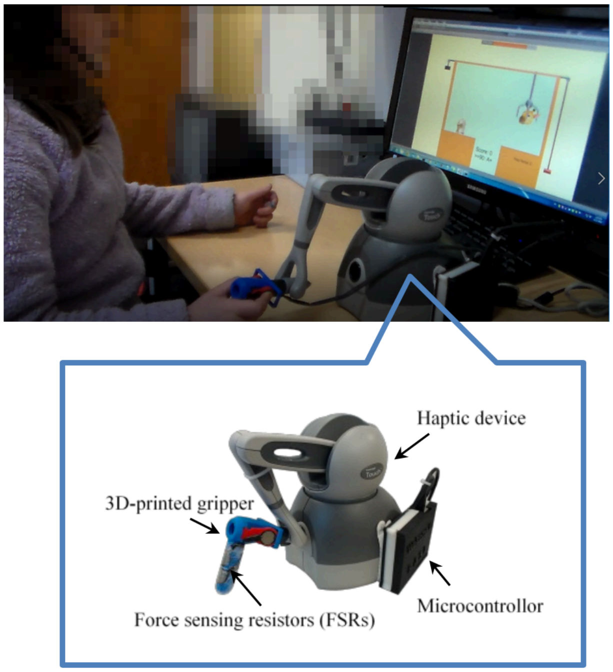


Figure 7-2. The use of Haptic Gripper in INC-Hg system.

In order to test the capabilities and effectiveness of INC-Hg, we revised and reused the task *Prize Claw* as described in the previous chapter. However, in this case, the TD partner is replaced by the intelligent agent. In the *Prize Claw* task, the user and the agent collaboratively control the claw to get as many prizes as possible. They are allowed to perform two manipulations with the Haptic Gripper, grip manipulation and movement manipulation (refer to Section 4.4.1 for more information about the use of Haptic Gripper). As shown in Figure 7-3, the user and the agent separately control a handle to move the claw based on a PD controller model (Figure 7-6). To make the claw go down, they both need to grip the Haptic Gripper using appropriate forces. Different forces could make the claw go to different depths. Every time, two kinds of toys are randomly selected and displayed in the claw machine, the user and the agent need to discuss which one they would like to get first. Thus, the game requires the user and the agent to communicate their intentions and synchronize their manipulations in order to succeed.

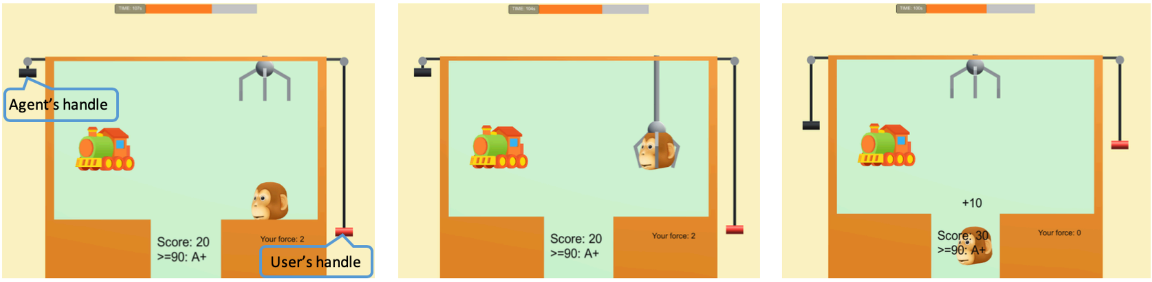


Figure 7-3. The *Prize Claw* Game. The user and the agent work together to move the claw to the target (left), and grip simultaneously to make the claw go down to grab the target (middle), and drop the target into the hole to get rewards (right).

7.4.2 Design of the Intelligent Agent

The intelligent agent was designed to 1) conduct flexible conversations with the user and 2) perform haptic interactions with the user. As shown in Figure 7-1, three major modules were developed to implement the functionalities of the intelligent agent.

7.4.2.1 Perception Module

The *Perception Module* was designed to gather specific user and CHVE data in order to help the agent to understand the scenarios. The *Speech Monitor* obtains the real-time speech audio data of the user, which are transcribed into texts in the *Speech-to-Text* module by using Google Cloud Speech-to-Text AP [37]. The *User Action Monitor* obtains the user's action data, such as the grip force data and position data, while the *Environment State Monitor* obtains the states of CHVE, such as the game time or the identity and the position of the virtual objects. All of these data are preprocessed in the *Perception Module* and sent to the *Process Module* to guide agent behavior.

7.4.2.2 Process Module

The *Process Module* was designed to extract and combine all of the information in the *Perception Module* to determine appropriate agent behaviors related to speech output and haptic interaction. In this module, we developed a *Speech Classifier* to recognize the dialogue acts of the user's speech, and an *Interaction Controller* to generate the agent's behaviors.

(1) *Speech Classifier*

Communication is an important skill used in collaborative tasks that can greatly influence agent behaviors. In our previous study where 10 ASD-TD pairs of children completed the collaborative *Prize Claw* task in a CVE (described in Chapter 7), we found through manual human coding that more than 99%

of conversations during the collaborative training were task-related. Therefore, we focused on designing an agent that could accurately understand domain-related speech, and would politely end an out-of-domain conversation with responses such as, "Sorry, I can only answer the questions related to the game". To enable the agent to understand the user's speech, we used Dialogue Act modeling to represent speech utterances using combinations of dialogue acts and slots [38]. A dialogue act (DA) represents the meaning of an utterance (e.g., a question or a request). DAs form a tag set that classifies utterances according to a combination of pragmatic, semantic and syntactic criteria. A slot is a variable that presents the specific information of the utterance. For example, a speech utterance ("Tell me the position of the object") can be classified as a *Request* DA with slots (*Position, Object)*. To define appropriate DAs for this system, we analyzed and used the collected conversation data from our previous study to build the text corpus and speech classifier. After analyzing the participants' conversations in the previous human-to-human *Prize Claw* tasks, we defined five classes of dialogue acts, which are described in Table 7-1. We also defined ten slots, such as *objectID*, *subject*, *object*, *action*, *force*, *accept*, *reject*, *salutation*, *question*, and *outOfDomain*. Each slot has several slot values. For example, the *objectID* slot words include all the possible names of the objects that can be presented in the game. An utterance's slot values are set by mapping each word of the utterance with all the predefined slot words.

Table 7-1. Dialogue Act Classes.

No.	Name	Description	Example
1	*Ack*	**Ack**nowledgement	Okay.
2	*ReqObj*	**Req**uest an **obj**ect	Which toy would you like to get?
3	*ProObj*	**Pro**vide the **obj**ect/information	The pig./ I am ready to drop.
4	*DirAct*	**Dir**ect partner to take some **act**ions	Move the claw to the pig.
5	*Que*	Ask **que**stions	How to get it?

We used 736 conversation data samples from our previous *Prize Claw* study to develop a *Speech Classifier* to compute the DA class of the user's speech. These sample data included 156 utterances labeled as class "*Ack*" (Acknowledgement), 146 utterances labeled as class "*ReqObj*" (Request an object), 154 utterances labeled as class "*ProObj*" (Provide the object/information), 150 utterances labeled as class "*DirAct*" (Direct an action), and 130 utterances labeled as class "*Que*" (Ask questions). With these sample data, we first evaluated several classical machine learning classifiers (e.g., Naïve Bayes, Random Forest, k-Nearest Neighbor, etc.), and found that the SVM-RBF had the best accuracy of 81%. Therefore, we developed the *Speech Classifier* using the SVM-RBF model based on the procedure as shown in Figure 7-4. First, some preprocessing tasks were performed on the input data, such as removing punctuation and replacing slot words with corresponding slot types. Then the Natural Language Toolkit (NLTK) [39] was used to extract word sequence features, such as unigrams, bigrams and POS-tagger [40]. Next, Principal Component Analysis (PCA) was performed to reduce the feature dimension (maintain five components) and generate a PCA model. Once the features were selected, we used the features and labeled sample data to train the SVM-RBF model. Finally, the trained SVM-RBF model and the PCA model and other feature information were saved in the system to classify the user's speech utterances in real time.

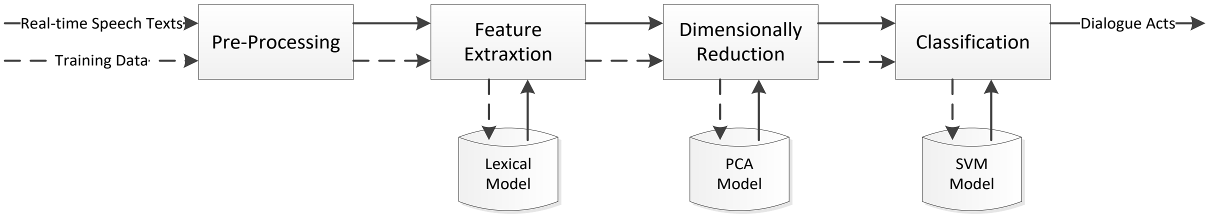


Figure 7-4. The Speech Classification Procedure.

(2) *Interaction Controller*

The classified speech data combined with the action and state data are then used by the *Interaction Controller* to determine the agent's conversation and interaction behaviors. The *Interaction Controller* is a finite state machine developed based on a pre-defined set of paired condition and action. Figure 7-5 shows the flow how the interaction controller addresses the perceived data.

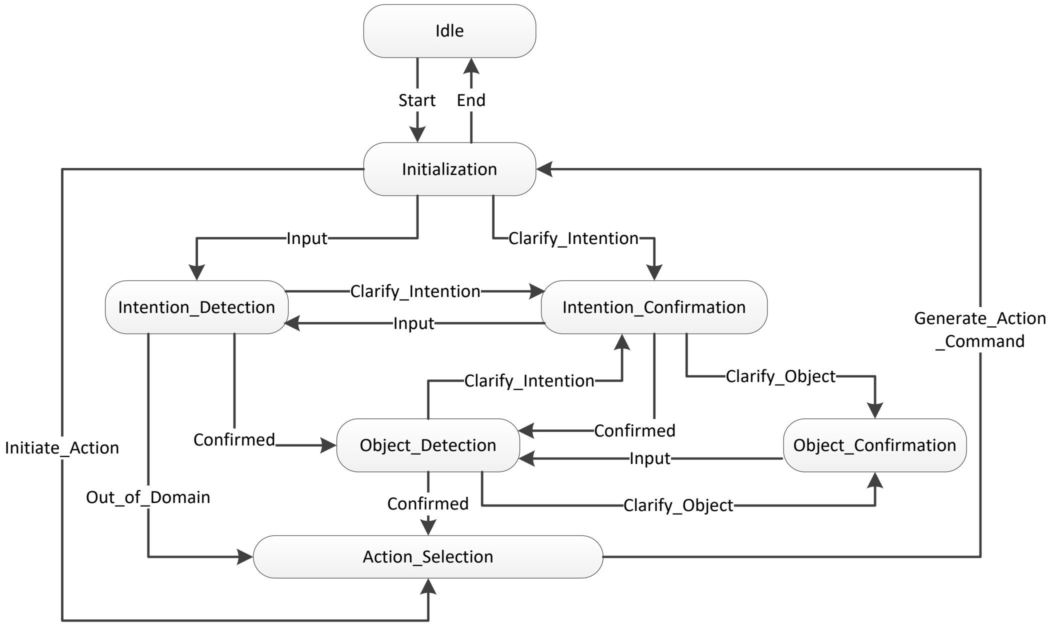


Figure 7-5. The *Interaction Controller* Module.

Based on the features of the collaborative *Prize Claw* task, the *Interaction Controller* recognizes the user's behavior by detecting the user's intention and associated target. An intention is an action the user would take or the user wants the agent to take (e.g., asking the agent to pick up an object). A target is a toy object the user intends to manipulate by the action. Initially, the *Interaction Controller* detects the user's intention with the recognized speech data, user's action data and task state data. If an out-of-domain intention is detected, a speech feedback would be generated to notify the user that the agent can only talk about the task-related information, and the controller would restart a new intention detection. Otherwise, the controller would consider all the recognized data to determine a valid and unambiguous intention, based on a series of pre-defined rules. For example, when the user says "Pig", the initial classification of the system might classify the user's intention as "*ProObj*". However, the system would combine this classification result and other contextual information (e.g., the status of the "pig" toy) to improve the intention detection results, in order to determine whether the user intended to pick up the "pig" toy, or to move the caught "pig" toy towards the hole. If the task state data indicates the claw has caught the "pig" toy, it is more likely that the user is asking the agent to move the "pig" toy towards the hole.

After the user's intention is determined, the *Interaction Controller* detects the associated target using the weighted average method. A target can be represented with a set of properties, such as whether the object exists in the machine (P_{exist}), and whether this is an active object the user is manipulating (P_{active}). We assigned each property with different weights to indicate the importance of the property (Table 7-2). One valid property for an object would contribute to the total final weights of this object ($W = W_{id} \times P_{id} + W_{active} \times P_{active} + W_{exist} \times P_{exist} + W_{last} \times P_{last} + W_{last1} \times P_{last1}$). The object with the highest weights is determined as the target.

Table 7-2. Property Weight Description.

Symbols	**Description**	**Values**
W_{id}	The weight for the object the user has mentioned in the conversation.	15
W_{active}	The weight for the object that is being manipulated.	10
W_{exist}	The weight for the object that exists in the claw machine right now.	3
W_{last}	The weight for the object that was manipulated last time.	5
W_{last1}	The weight for the object that is the last object left in the claw machine.	10

In addition to the *Intention Detection* module and *Object Detection* module, we also developed the *Intention Confirmation* module and the *Object Confirmation* module to let the user provide more information to clarify their intention and target, or respond to the agent to confirm an action. Specially, the agent can initiate a conversation with the user and/or perform a haptic interaction with the user to provide information and guidance to the user, when no intention is detected within a period or when the user performs wrong operations (e.g., drop the object on the table).

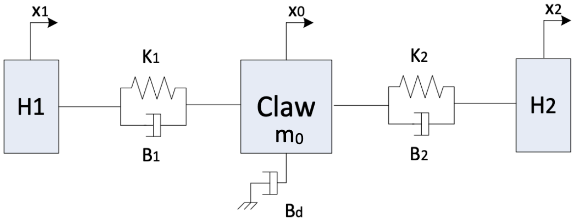
Each detected-intention/detected-target pair is mapped to a specific agent action based on the pre-defined rules in the *Action Selection* module. The action could be a pure speech feedback, a pure operation feedback, or a speech-operation feedback. For example, when the user asks, “How can we get it?”, the agent can provide speech feedback such as, “We should both grip hard to make the claw go down to get it.” When the user pulls/pushes the claw far from the target, the agent can automatically adjust the agent’s handle to move the claw to the target as closely as possible. However, when the agent has moved the handle close to the border of the machine and only the user can move the handle to adjust the position of the claw, the agent would generate a speech guidance to direct the user to move the handle to the appropriate position (e.g., “Move your gripper up”).

When the user does not provide any intention, target or response within a certain time, the agent will first try to ask the user’s intention (e.g., “Which one do you like to get now?”). If no intention is detected, the agent will randomly recommend a target (e.g., “Do you want to get the pig?”) to the user. If no feedback is detected, the agent will invite the user to get the target (e.g., “Let’s get the pig!”). At the same time, the agent would move the claw towards the toy monkey and the user would see the agent’s operation and feel the interaction force. Therefore, the agent was designed to behave at the user’s pace, but would take the leadership role when the user is less active.

Additionally, in order to provide diverse speech feedback to more closely mirror a naturalistic peer interaction, a speech lexicon was built to store multiple speech to text presentations for each possible speech semantic. For example, a representation can be randomly selected for the speech semantic (“Request a target”) from these representations: “What would you like to get now?”, “Which toy do you want to get?” or “Do you want to get the pig or the monkey?”.

7.4.2.3 Actuation Module

The agent *Actuation Module* includes a *Text-to-Speech* (*TTS*) module to transfer the agent’s speech texts to speech audios, which are played to the user. The *TTS* module was implemented by using the Microsoft Azure text-to-speech API [41], which can be easily integrated with Unity 3D. A *PD Controller* was developed to simulate the interaction between the user and the agent to collaboratively manipulate the claw (Figure 7-6). To design the *PD controller*, we first simulated it using MATLAB to find appropriate parameters (Table 7-3). The *PD controller* accepts the user input as well as the commands from the agent *Process Module* (e.g., adjusting the force or the handle position to move an object) to execute specific actions (e.g., moving the claw or making the claw go down), which would affect the states of the user and/or the virtual object. The *Haptic Feedback Generator* module monitors the agent’s actions and generates appropriate haptic interaction feedback to the user. For example, when the agent moves the handle and changes the position of the claw, the user would feel the pulling or pushing force calculated by the *PD Controller* as shown in Figure 7-6. When the agent and the user pick up an object, the user feels the weight of the object.



$$F_1 = K_1(x_0 - x_1) + B_1(\dot{x}_0 - \dot{x}_1)$$
$$F_2 = K_2(x_0 - x_2) + B_2(\dot{x}_0 - \dot{x}_2)$$
$$m\ddot{x}_0 = -F_1 - F_2 - B_d\dot{x}_0$$

Figure 7-6. The PD Controller for Claw Manipulations. The virtual haptic handles are represented by H1 and H2. The virtual couplers between the virtual claw and the haptic handles are represented by K1, B1, K2 and B2. The interaction forces are represented by F1 and F2.

Table 7-3. PD Controller Parameters.

Symbols	**Values**
m_0	$1\ kg$
H_1, H_2	$0.035\ kg$
K_1, K_2	$5\ N/cm$
B_1, B_2	$0.03\ N \cdot s/cm$
B_d	$0.25\ N \cdot s/cm$

7.5 Usability Study

We conducted a usability study to (1) investigate the acceptability of the intelligent agent among the children with ASD, (2) to evaluate the capability of intelligent agent in terms of the accuracy of speech recognition and response, and (3) to assess the usefulness of INC-Hg as a social interaction platform to foster communication and collaborative interaction between the agent and the participants.

In order to explore the performance differences of participants when they performed the similar collaborative tasks with a human and with an agent, we recruited 10 children with ASD who participated in our previous study and played a similar *Prize Claw* game in the human-to-human interaction mode (refer to Chapter 6). The participants' information is shown in Table 7-4. All the participants with ASD met the autism spectrum cutoff on the Autism Diagnostic Observation Schedule-Second Edition (ADOS-2) [42]. The Stanford-Binet Intelligence Scales, Fifth edition (SB-5) [43] was employed to measure the intellectual functioning (IQ) of the participants, while the Social Responsiveness Scale, Second Edition (SRS-2) [44] and the Social Communication Questionnaire – Lifetime score [45] were completed by participants' parents to index the ASD symptoms of their children.

Table 7-4. Participant Characteristics (N = 10)

Metrics	**ASD Group Mean (SD)**
Age (years)	10.94(1.36)
IQ	93(18.53)
SRS-2 total raw score	103.25(21.76)
SRS-2 T-score	79(8.14)
SCQ Lifetime total score	21.75(7.38)
ADOS-2 total score	17.88(3.97)

Each participant attended one session in one day. At the beginning of the session, experimenters explained the procedure and played an introduction video about how to interact and communicate with the intelligent agent in the system. Then the participants played the *Prize Claw* game twice, each of which took 3 minutes to finish. At the end of the session, they completed a survey to give their feedback. Detailed information of participants can be found in Appendix A of Chapter 6.

7.6 Results and Discussions

The study results indicated that the INC-Hg system was well accepted by children with ASD and was able to support smooth human-to-agent conversation and interaction. Here we present results regarding the acceptability of the INC-Hg system among children with ASD, the system performance, and the user performance.

7.6.1 Acceptability of the INC-Hg System

We collected participant feedback about the agent, the game and the haptic effects using 11 questions scored along a 5-point Likert scale. Table 7-5 shows the survey questions as well as the participants' responses.

The responses to questions 1-2 indicated that most participants liked to play with the agent and felt that it was not difficult to learn how to communicate and interact with the agent. The responses to questions 3-4 indicated the participants and the agent could understand each other well. The responses to questions 5-6 indicated the agent could respond timely and correctly. The responses to questions 7-9 indicated that participants enjoyed the virtual game and the game could promote communication and cooperation between the participant and the agent. The responses to questions 10-11 indicated that participants liked the haptic effects and half of them thought the haptic effects were useful to help them understand their and agent's manipulations. All the user feedback suggest INC-Hg was well accepted among the children with ASD.

Table 7-5. Survey Feedback of Participants with ASD (N = 10)

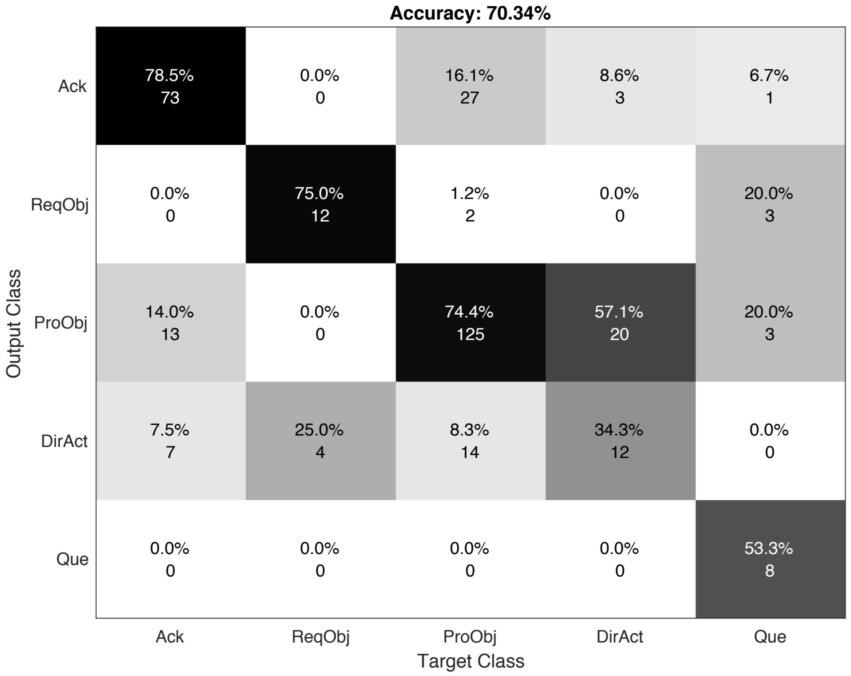
No.	Questions	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	Mean(SD)
1	How much do you like to play the games with the agent? (5-very much, 1-not at all)	5	2	5	2	5	4	3	5	4	4	3.9 (1.2)
2	How difficult was it to play with the agent? (5-very difficult, 1-very easy)	1	4	3	3	1	3	2	2	3	2	2.4 (0.97)
3	How well did the agent understand you? (5-excellent, 1-very bad)	4	3	3	3	5	3	4	4	3	5	3.7 (0.82)
4	How well did you understand the agent? (5-excellent, 1-very bad)	5	3	3	4	5	4	4	5	4	4	4.1 (0.74)
5	Did the agent respond to you quickly enough? (5-very quick, 1-very slow)	3	2	4	2	5	4	3	3	4	4	3.4 (0.97)
6	How often did the agent respond to you appropriately? (5-almost always, 1-never)	4	2	4	3	4	4	4	5	3	4	3.7 (0.82)
7	How much did you like the game? (5-very much, 1-not at all)	3	4	5	3	5	5	4	5	2	4	4 (1.05)
8	How important was it to talk to the agent in order to win the collaborative game? (5-very important, 1- absolutely useless)	5	3	4	4	5	4	4	4	4	5	4.2 (0.42)
9	How important was it to work together with the agent in order to win the collaborative game? (5-very important, 1- absolutely useless)	3	3	4	5	3	4	5	4	4	4	3.9 (0.74)
10	How much did you like these haptic effects? (5-very much, 1-not at all)	5	2	5	1	5	4	4	3	3	4	3.6 (1.35)
11	How useful are these haptic effects to help you understand your operations or the agent's operations? (5-very useful, 1-absolutely useless)	4	1	5	1	5	4	2	5	2	4	3.3 (1.64)

7.6.2 System Performance

INC-Hg automatically recorded the task-related data from 20 games and 60 minutes of game data (10 participants × 2 games × 3 minutes per game) of the study. This yielded a total of 327 socially-directed participant utterances and a total of 558 agent utterances, which means that participants said an average of approximately five utterances per minute. The frequent utterances suggest that the game was well designed to promote verbal communication.

To evaluate the classification accuracy of the system, we recruited two human coders (trained graduate students with experience collecting and analyzing qualitative and quantitative data) to manually classify the recorded utterances of participants into the five dialogue act classes as the ground truth. We provided a framework that described the concrete definitions of the five dialogue act classes and a few examples about how to read and code the recorded files for the human coders. Each human coder independently coded all the data. After each rater completed coding, a percent agreement of 93.5% was found. For the coding that were not in agreement, two human coders reconciled differences via a consensus in which any discrepancies were discussed and resolved.

Figure 7-7 shows the confusion matrix of the dialogue act classification results. The results indicated that the classification accuracy of the system reached 70.34% (230 out of 327 utterances were accurately classified), which is much higher than the random classification accuracy for five classes (20%). From the matrix, we see that most "*DirAct*" utterances were mistakenly classified as "*ProObj*" (57.1%). The reason might be that participants usually mentioned the name of the target object when giving the action commands (e.g., pick up the pig). The classification results suggested the potential of INC-Hg to automatically recognize and analyze the conversation content.



Accuracy: 70.34%

Output Class \ Target Class	Ack	ReqObj	ProObj	DirAct	Que
Ack	78.5% 73	0.0% 0	16.1% 27	8.6% 3	6.7% 1
ReqObj	0.0% 0	75.0% 12	1.2% 2	0.0% 0	20.0% 3
ProObj	14.0% 13	0.0% 0	74.4% 125	57.1% 20	20.0% 3
DirAct	7.5% 7	25.0% 4	8.3% 14	34.3% 12	0.0% 0
Que	0.0% 0	0.0% 0	0.0% 0	0.0% 0	53.3% 8

Figure 7-7. The Confusion Matrix for Dialogue Act Classification.

In order to analyze the accuracy of the agent to respond to the user, as well as the accuracy of the agent to initiate a proper conversation and/or interaction with the user, two human coders were also asked to watch the videotapes to code the participant's and agent's utterances into two types of utterances, *Initiation* and *Response*. *Initiation* represented one player's statement that started a conversation. *Response* represented one player's feedback to the partner's statement. The inter-rater reliability using the same procedures described above was 100% for this process.

Based on the final coding data, we counted the frequencies of proper/improper *Initiations* and *Responses* of the agent (Table 7-6). The results indicated that among the 558 agent's utterances, 312 utterances are *Responses*, while 246 ones are spontaneously initiated utterances. We found 88.46% (276 out of 312) of agent's *Responses* were proper feedback to the participants' speech or actions. However, there were 7 times when the agent did not give any response to the participants' requests, reducing the accuracy to 86.52% (276 out of 319). On the average, the proper *Response* rate to each participant was 87.40% (SD: 0.11). The *Response* accuracy is comparable to those of existing conversational agent systems [46-48]. For example, the conversational agent, Max, developed by Kopp et al. can act as a museum guide to provide information to visitors. The agent can accurately respond to 63% of 50423 visitors' natural language inputs [46]. The conversational intelligent tutor, Oscar, developed by Latham et al. can lead a tutoring conversation and dynamically predict a student's learning style with an accuracy of 61-100% [47]. In addition, 97.56% (240 out of 246) of the agent's *Initiations* were found to be proper *Initiations*. On the average, the proper *Initiation* rate to each participant was 96.54% (SD: 0.10). All the six improper initiations occurred when the participants and the agent initiated conversations about the same time. For example, the participant might say "Let's get the pig" right after the agent started a speech, "What do you want to get now?" Though the system could recognize the participant's intention and send the agent's handle movement commands quickly, the agent's speech audio "What do you want to get now?" had to be completely played before the next agent's speech audio "Okay. I am moving to the pig" could be played. We would add the functionality to control the play, pause and stop of agent's speech audios in the next version of INC-Hg. Despite this weakness, the results still indicated that the agent was able to provide appropriate instructions, recommendations and answers, and act appropriately to interact with the participant at the right time. These results also indicated that though the initial classification accuracy was only 70.34%, INC-Hg could improve the agent's communication accuracy to 91.33% (516 proper utterances out of 565 total utterances) by considering the contextual information. A sample of user-agent conversations is showed in Table 7-7.

Table 7-6. The Response Accuracy and Initiation Accuracy of Agent.

Agent's Utterances	**Proper**	**Improper**	**Total**
Response	276 (86.52)	36 + 7(No response)	319
Initiation	240 (97.56%)	6	246
Total	516 (91.33%)	53	565

Table 7-7. A Sample of Human-to-Agent Conversations.

User: Now what do you want to get?
Agent: Let's get the pig.
User: Okay.
(*The user does not move the gripper for a while.)*
Agent: Move your gripper down.
User: Okay. (*The user moves her gripper down.)*
Are you ready to get the pig?
Agent: Yes. (*Both grip to make the claw down to get the pig.)*
(*The user does not use the appropriate force when they are trying to get the pig.*)
Agent: We should squeeze slightly to get the pig.
User: Okay. (*The user adjusts the force and gets the pig successfully.*)
(*The user inadvertently releases the gripper and drops the pig on the table.*)
Agent: No, pick up it again.
User: (*The user moves the gripper and tries to pick up the pig again.*)

7.6.3 Player Performance

We compared the participant performance when using this INC-Hg system with their performance when using the C-Hg system in our previous study. In the previous study of Chapter 6, the same participants took the similar *Prize Claw* tasks with TD partners in a pre-test and a post-test. Here we compared the human-to-agent performance results to those of human-to-human performance results obtained from the pre-test of the previous study, since this was the first time the participants used the INC-Hg System (Table 7-8).

The performance analysis indicated that the participants and the agent performed collaborative operations together an average of 61% of the game time, which was higher than the average collaborative ratio (40%) of the previous human-to-human interaction study. This result suggested the effectiveness of INC-Hg system in supporting collaborative operations between participant and the agent.

In addition, the average frequencies for *Initiations* and *Responses* of the participants with ASD are comparable in both studies, and no significant differences were found (Table 7-8). The Spearman's rank correlation analysis also found medium correlations between the *Responses* ($\rho = 0.32, p = .367$) and between the *Initiations-Responses-Ratio* (ρ = 0.406, p = .244) of participants with ASD in two studies, which suggested that the agent was able to induce similar conversation patterns in the participants that were similar to the human partner.

As for the partners, the average *Initiation* frequencies of the TD partners and the agent were comparable, and a strong correlation was found (ρ = 0.645, p = .044). However, compared to TD partners, the agent provided significantly higher responses ($p < .001$, $|r| = .744$). This reflects that the agent was designed to actively communicate with the participant and always provide feedback to the participant's speech or actions. In addition, the agent had significantly lower *Initiations-Responses-Ratios* ($p < .001$, $|r| = .822$), since the agent was designed to encourage the participant to actively initiate conversations and interactions instead of passively accepting commands from the partner. Therefore, the agent monitored the performance of the participant and initiated communications/interactions only when the participant performed wrong operations (e.g., dropping the target) or when the participant did not perform any operations for a while (e.g., 8 seconds).

The strong positive correlation between the *Initiation* frequency of participant with ASD and the *Response* frequency of the agent (ρ = 0.659, p = .038), the strong negative correlation between the *Initiation* frequency of participant with ASD and the *Initiation* frequency of the agent (ρ = -0.755, p = .012), and the strong negative correlation between the *Initiations-Responses-Ratios* of the participants with ASD and the agent (ρ = -0.806, p = .005) also suggested that the agent was able to provide active responses, allow the participant to lead the collaborative operations and only provide help when needed. Compared to TD participants, the agent partner was designed to grant the user enough time and freedom to explore the task rules and figure out his/her manipulations, and to adjust the agent's behaviors based on the user's performance (e.g., reducing the agent's *Initiation* frequency when the user is initiating most conversations.)

Table 7-8. The Comparison of User Performance with C-Hg (human-to-human mode) and with INC-Hg (human-to-agent mode).

Metrics (/each game)	**Human-to-Human (C-Hg)**		**Human-to-Agent (INC-Hg)**	
	ASD (Mean/SD)	**TD (Mean/SD)**	**ASD (Mean/SD)**	**Agent (Mean/SD)**
CollaborativeRatio	0.40 (0.17)		0.61 (0.13)	
Initiation	11.5 (6.24)	15.95 (9.02)	9.65 (5.85)	12.3 (3.38)
Response	7.2 (4.92)	6.45 (4.24)	7.4 (2.79)	15.6 (5.13)
IniResRatio	3.89 (5.84)	3.69 (3.05)	1.81 (1.83)	0.93 (0.53)
Total	18.7 (8.52)	22.4 (13.03)	17.05 (4.96)	27.9 (3.04)

IniResRatio, the ratio of Initiation frequency to Response frequency

7.7 Conclusion and Future Work

We designed and developed an Intelligent Collaborative Haptic-Gripper system (INC-Hg) that includes an agent to automatically communicate and perform collaborative interactions with the user by recognizing the user's behavior and task information in real time. Results indicated that INC-Hg can perform real-time communication pattern analysis based on the recognized speech data and record specific performance metrics (e.g., collaborative ratio), which can greatly improve the efficiency of conversation and performance analyses. Participants with ASD reported that they liked to perform the collaborative tasks with the agent and enjoyed the haptic interaction with the agent, supporting system usability and tolerability within this population. Results also indicated that the system could classify the participant's utterances into five classes with the accuracy of 70.34%, which suggested the potential of INC-Hg to automatically recognize and analyze conversational content. The results also indicated high accuracies of the agent to initiate a conversation (97.56%) and respond to the participants (86.52%), suggesting the capability of the agent to conduct proper conversations with the participants. For all the participants, that was the first time that they performed a collaborative task with an agent partner. However, they still showed a good collaboration with the agent partner. Compared to the results of human-to-human collaborative tasks, the human-to-agent mode achieved a higher average collaborative operation ratio (61% compared to 40%), and comparable average frequencies for *Initiations* and *Responses* among the participants with ASD, which offered the preliminary support as well as areas of improvement regarding the agent's ability to respond to participants, work with participants to complete tasks, and engage in back-and-forth conversations, and suggested the potential of the agent to be a useful partner for individuals with ASD completing CVE tasks. As in our previous study, participants once again reported that they enjoyed the haptic gripper.

The methods and components used to develop INC-Hg can be easily transferred to other domain-specific systems by modifying the three modules of the agent. For a new task, the major changes needed are to update the *Speech Classifier* by collecting new conversation sample data and specifying new speech utterance classes for the new task, and to modify the *Interaction Controller* by specifying new interaction rules based on the specifications of the new task.

In the future, we want to continue our work to explore whether INC-Hg could help children with ASD to generalize the learnt skills into a natural environment. First, we would improve the functionality of agent's speech audio player to ensure the agent could provide 100% of proper initiations. Second, most of "*DirAct*" utterances were classified into the "*ProObj*" class in this study. We would consider new effective features to distinguish these two classes, or combine these two classes into one class considering that the results of both classes usually led to a manipulation action in this specific *Prize Claw* task. Next, since INC-Hg was reported as well received among the children with ASD in this usability study, we plan to conduct a multi-session study with a larger number of participants to evaluate the influence of INC-Hg on users' performance, and the capability of INC-Hg to automatically measure performance change based on the recorded metrics. Currently, INC-Hg only contains one collaborative fine motor skill training task. We plan to develop more collaborative tasks that provide practice opportunities of multiple skills (e.g., eye gaze, motor skill) of children with ASD. In addition, we want to collect more out-of-domain training data to develop a more efficient model for out-of-domain utterance detection, as well as to make the agent have the capability to conduct a number of interesting out-of-domain conversations (e.g., jokes) with the user.

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CHAPTER 8

CONTRIBUTIONS AND FUTURE WORK

In recent years, computer-assisted systems have been increasingly employed to support a wide range of psychological activities from therapy to the training of specific skills. This dissertation describes my research on the design, development and application of Virtual Reality (VR) -based computer-assisted systems for Autism Spectrum Disorder (ASD) intervention. With the capability of providing engaging and low-cost intervention environment, VR-based computer-assisted systems show the potential as an alternative intervention paradigm to reduce the burden of ASD resources and expand accessibility to effective ASD interventions.

8.1 Contributions

Previous studies on computer-assisted systems mainly focused on understanding and improving social communication and interaction deficits of children with ASD. Most of these studies used computer programs to provide restricted interactions between the user and the computer, and were not able to scale up well for complex adaptive interactions and thus led to weak transfer of learnt skills into real scenarios. In addition, few studies were conducted on the motor impairments of children with ASD, especially by taking advantage of advanced technology. However, the high prevalence of motor impairments has been found among ASD population and children with ASD show motor coordination deficits and delays in fine motor skills compared to their typically developing (TD) peers. Although a few studies proposed that fine motor skill might affect social skill practice of children with ASD, the relationship of both skills are still underexplored. The work presented in this dissertation was designed to address these issues and to provide more efficient and adaptive training systems for ASD intervention: (1) developing Collaborative Virtual Environment (CVE) systems that support realistic interactions and flexible conversations between remote users, (2) developing VR-based systems with haptic device that support the assessment and training of fine motor skills of users as well as the investigation of the impact of fine motor skill on the social skill of the users, and (3) developing an intelligent agent that supports human-to-agent communication and interaction within the VR-based fine motor training system.

The first set of technical contributions is in the design and development of CVE systems for fostering social skills of children with ASD. Most existing CVE systems for ASD intervention only support face-to-face interactions in a co-located environment or only provide sequential interactions (i.e., users take actions by turns). We designed a CVE system (Hand-in-Hand) that supports remote interaction with both sequential and simultaneous interactions (i.e., users take actions with the help of the partner). This system integrated with a hand tracking device, Leap Motion, offer a chance for users to control the virtual game elements in the CVE with their hands. The Statechart diagram was used to model the dynamic functionality of the system. A study with six children with ASD and six TD children indicated improved performance of participants in cooperation and communication. In order to foster information sharing and communication, we improved the CVE system by integrating a communication-enhancement module to provide gaze- and voice-based communication strategy. The new mode slowed down the pace of the game and created more opportunities for users to pay attention to their partners and communicate with each other. Six ASD/TD pairs of participants were recruited for the evaluation of this system. It was found that participants using this system achieved greater improvement regarding cooperation and communication, compared to those using the CVE system without the newly integrated module. The two CVE systems indicate the success of our systems in supporting collaborative interactions between remote users, inspiring realistic cooperation and flexible communication, and objectively assessing the user's performance.

The second set of technical contributions is in the design and development of VR-based systems for assessing and training fine motor skills (hand movement and grip force skills) of children with ASD. Most existing technical systems for studying the fine motor ability of children with ASD only target the movement abnormalities and ignore the importance of grip control. These systems often employ the optical motion tracking system with markers attached on the user to obtain the motor information, which are not well tolerated by children with ASD. We designed a tablet system to assess the hand usage of children with ASD in movement manipulations, which could provide non-invasive access to the hand movement information of the user. The system provided fine motor tasks that could be played by one player using two hands or by two players each of whom using one hand. Four children with ASD and four TD children were recruited to test the system. The study results demonstrated the difference between the ASD group and the TD group in hand usage. We also designed a haptic-gripper VR system (Hg) that provided the opportunities for assessing and practicing the hand movement manipulation and grip force manipulation at the same time with a series of virtual handwriting-like tasks. It took the advantages of the haptic device to increase immersion and quality of task performance and thus had the possibility of enhancing the training achievements. A usability study with six children with ASD and six TD children was conducted to analyze the impact of the system on the participants and the usefulness of the proposed performance metrics for assisting fine motor skill assessment. The study results indicated that the proposed metrics could be useful to quantify the fine motor skills, and the participants showed improved performance after using the system. In addition, features extracted from the performance data were found to be useful for distinguishing participants with ASD from TD participants with the accuracy up to 80%. These findings lend support to the promising potential of our system for fine motor skill analysis and training for individuals on the autism spectrum, which might expand the accessibility of efficient fine motor interventions.

The third set of technical contributions is in the design and development of a collaborative haptic VR system (C-Hg) for children with ASD to simultaneously practice fine motor skill and social skill. This work investigated how the fine motor skills (hand movement and grip force skills) impact the social skills (social communication and interaction skills) of children with ASD, which is underexplored among the ASD research. We first performed the comparative analysis of the control architectures for collaborative haptic virtual environments to choose an appropriate architecture and parameters for implementing a reliable and stable distributed training system. With a simulated CHVE using MATLAB, three control architectures were tested in terms of the frequency response, the position error and the force rendering under different network delays. The experimental results indicated that the centralized control architecture and the wave-variable-based control architecture achieved better performance. We then implemented a collaborative fine motor skill training system with the centralized control architecture. The system can provide grip force skill training, hand movement skill training and complex fine motor manipulation training (involving both hand movement and grip force manipulations) in individual or collaborative human-to-human interaction mode. A usability study with 10 pairs of children with ASD and their TD peers was conducted to evaluate this system. The study results indicated that both ASD children and TD children showed significant improvements on the VMI pre- and post-test, reflecting the relevance of the task to standardized real-world motor assessment tools. Participants in both groups also showed significant improvements in performance during individual and collaborative tasks, which suggests that this system not only impacts individual fine motor skills, but also fosters social communication and collaboration. We also found strong/medium correlations between individual task performance and collaborative task performance, indicating that improved individual fine motor skills relate to better performance in social collaborative tasks. In addition, participants with ASD were found to conduct more collaborative manipulations and initiate more conversations with their partners in the post-test, suggesting that more active collaboration and communication of participants with ASD happened after practicing in the individual fine motor tasks. These results demonstrated that fine motor skill practice might have positive impacts on communication and collaboration skills of participants with ASD in the collaborative tasks.

In addition, in order to enable adaptive training and autonomous conversation pattern analysis, we developed an Intelligent Collaborative Haptic-Gripper VR System (INC-Hg) to provide an AI agent who can understand, communicate and haptically interact with the user during the collaborative fine motor training tasks. This system is able to record the real-time recognized conversation data and performance data, and therefore can greatly reduce the resource burden of communication and interaction performance analysis. We conducted a usability study with 10 participants with ASD to test the acceptability of this system and functionality of the agent. Participants with ASD reported that they liked to perform the collaborative tasks with the agent and enjoyed the haptic interaction with the agent, supporting system usability and tolerability within this population. Results also indicated that the system could classify the participant's utterances into five classes with the accuracy of 70.34%, which suggested the potential of INC-Hg to automatically recognize and analyze conversational content. The results also indicated high accuracies of the agent to initiate a conversation (97.56%) and respond to the participants (86.52%), suggesting the capability of the agent to conduct proper conversations with the participants. Compared to the results of human-to-human collaborative tasks, the human-to-agent mode achieved higher average collaborative operation ratio (61% compared to 40%), and comparable average frequencies for *Initiations* and *Responses* among the participants with ASD, which offered the preliminary support as well as areas of improvement regarding the agent's ability to respond to participants, work with participants to complete tasks, and engage in back-and-forth conversations, and suggested the potential of the agent to be a useful partner for individuals with ASD completing CVE tasks.

Besides these technical contributions, the work presented in this dissertation also contributes towards the science of ASD intervention by providing controllable and adaptive intervention environments where different intervention paradigms can be assessed with objective measurements. Such technologically sophisticated systems are expected to play an important role in addressing the lack of access to trained clinicians and reduce overall cost of treatment. The work in this dissertation provides important insights into how computer-assisted systems can assist and optimize ASD intervention and science.

8.2 Future Work

Though the presented work in this dissertation is promising, the results should be interpreted within the context of several limitations. First, the relatively small sample size, short intervention duration of the studies and the absence of a control group undermine the generalizability of the results. In the future, more participants, training sessions and matched control groups will be needed to strengthen the statistical analyses. In addition, future research should take into account the heterogeneity in performance within and individual differences framework. Second, though fine motor skills (hand movement and grip force control skills) were showed to positively impact social communication and interaction performance of users in collaborative tasks, more specific tasks and metrics should be developed to explore the underlying relationships. Third, the systems currently only track and evaluate a few skills, such as social conversation skill, haptic interaction skill, hand movement skill and grip force control skill. Considering the complexity of social interaction in daily life, tasks to practice other skills, such as gross fine motor skill, social empathy and facial expression recognition, could be developed and integrated. In addition, since the AI system was found to be well received among the children with ASD and was useful to speed up performance evaluation, the future work can further explore new features and functionalities that can enable the AI system to provide individualized training plans. Advanced technologies, such as deep reinforcement learning and cloud technology, can be applied to improve the intelligence of agent, provide a variety of interaction platforms and modes, and effectively record and analyze individualized data.