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A Feasibility Study of Eye Gaze with Biofeedback in a Human-Robot Interface

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ABSTRACT

Play is a vital activity in which children learn skills and explore the environment through object manipulation. Assistive robots have been used to provide access to play, and Forbidden Region Virtual Fixture (FRVF) guidance at the user interface could help the users make the robot traverse the play environment more efficiently because it behaves like virtual walls to follow. Eye gaze was used to indicate the user's intended target and generate the location of the virtual walls in a card sorting task. We eliminated the typical computer screen required for visual feedback to confirm gaze location, and examined the use of alternative feedback. In this feasibility study, first a group of adults without physical impairment tested the system with auditory and vibrotactile feedback modalities for the gaze fixation and with the virtual walls on and off for robot movement. Then case studies with children and individuals with physical impairments were performed. Even though gaze fixation feedback and the virtual wall did not improve the performance of adult participants without impairment, the feedback increased the speed and accuracy of the gaze fixation and the virtual walls improved the movement efficiency for the participants with impairment and a 6-year-old child without impairment.

Introduction

A child who has physical impairment may encounter pro- blems in terms of accessing play in, for example, reaching, grasping, and moving objects, which can result in develop- mental delays across different areas (Robins et al., 2012). Children with physical impairment frequently end up watch- ing play instead of joining in, as others will frequently handle the play objects on their behalf (Blanche, 2008). If children cannot perform independent play, they may miss opportu- nities to try things, show what they know and learn from their mistakes (Harkness & Bundy, 2001).

Children with physical impairment may be able to manipu- late play objects by controlling robots such as the Lego robot (Rios-Rincon, Adams, Magill-Evans, & Cook, 2016) or the Play-ROB (Kronreif, Prazak, Kornfeld, Hochgatterer, & Furst, 2007). These robots were controlled by multiple single switches in the case of the Lego robot and by a joystick in the case of the Play-ROB. Joysticks are the most intuitive interface to control robots (Harwin, Ginige, & Jackson, 1988), however, children who have severe physical impairments may not be physically able to manipulate joysticks.

Kinesthetic guidance through the user interface might help children to achieve joystick control of the robot in spite of their impairments. In a study by Atashzar et al. (2015), an adult with physical impairment operated a user-side robot (similar to a joystick interface) that controlled a task-side robot to perform a pick and place task. One feature of the haptic capabilities of the system was to allow forces occurring at the task-side robot to be felt at the user interface, which is important because it allows the user to perceive properties of objects. Other features of the system were filtering and scaling, so involuntary movements at the user interface were filtered out and the range of motion was enlarged at the task-side robot.

Haptics can also be used to provide guidance to the user to better control the robot. One form is motion guidance, which helps guide the user along a specified pathway, but there are risks associated with putting energy into a system, potentially causing it to go unstable (Abbott, Marayong, & Okamura, 2007). A safer method is a haptic system that limits the user's hand motion into a defined region using software generated virtual walls, which are so-called Forbidden Region Virtual Fixture (FRVF), so that the interface can help the users traverse the regions inside the walls of the virtual fixture and be restricted from going outside of the walls (Abbott et al., 2007). In our previous study a computer vision system was used for defining the location of the virtual walls based on visual information about the color and shape of the task targets, so the users could rely on the virtual walls while they sorted objects into the correct target destinations (Sakamaki, Adams, Gomez, et al., 2017). Ten non-disabled participants and one participant with physical impairments used the system, which restricted their hand movement to the defined region between the pick-up and correct drop-off locations during robot operation in the sorting task. However, the virtual walls gen- erated by the computer vision system did not allow the participants to make mistakes. Thus, the system is not suitable to be used for situations such as assessments to test skill levels or games to compete for a score, which require allowing a user to make mistakes.

Eye gaze fixation can be used to generate virtual walls according to the user's own choice. Eye gaze is easier to set up than other access methods that can detect user intention, such as brain-computer interface methods, has less influence from environmental noises (e.g., power line noise or electromagnetic noise), and requires less training. Detection of eye gaze fixation is commonly used for selecting an object of interest on a graphical computer interface. Typically, visual feedback, such as a mouse pointer on a screen, is used to help the user to sustain eye movement on a target, because it informs the user how the system is interpreting the gaze. One of the technical difficulties of eye gaze interfaces is distinguishing between spontaneous eye movements for gathering visual information and intentional eye movements for explicit selection, which is known as the Midas' touch problem (Møllenbach, Hansen, & Lillholm, 2013). In order to avoid unintentional selection, gaze fixation at the target of interest is needed for a prolonged period of time (the so-called dwell time). An eye gaze system such as this was used by children as young as three years old to control Lego robots in pick and place tasks. However, it was difficult for children to switch their attention between the screen, the robot, and back to the screen to accomplish tasks (Encarnação et al., 2017). For an eye gaze interaction application that does not involve a display, such as direct target selection in a physical play environment, another form of feedback is needed. Visual and auditory feedback has been used to augment visual feedback on on-screen computer tasks (Majaranta, MacKenzie, Aula, & Räihä, 2006). Auditory or vibrotactile feedback could be helpful to perform a task in a physical environment without a screen. It has been utilized for guidance of robot control (Rossa, Fong, Usmani, Sloboda, & Tavakoli, 2016), and could be alternatives to visual feedback for gaze interaction.

In the current study, auditory and vibrotactile feedback modalities for confirming target selection were implemented with a haptics-enabled robotic platform in a sorting task. The system allowed the user to select the target drop-off location in the physical environment by fixating their gaze on it, which in turn activated the virtual walls guidance to limit the user's robot trajectory from the pick-up to the drop-off location, even if it was a mistake. The task was performed first by a group of adults without physical impairment to examine the feasibility of the system, and then in case studies with children and individuals with impairments, a pragmatic mixed methods approach (Higginbotham & Bedrosian, 1995). Task performance was examined to see if the feedback about gaze fixation was helpful in selecting the target and if virtual walls guidance was helpful in moving between pick-up and drop-off locations. The research questions of this study were: (1) Can auditory feedback or vibrotactile feedback about gaze fixation location make target selection in the sorting task faster than without it? (2) Can the virtual walls, determined by the gaze-based target selection, improve movement efficiency of the robot operation compared to without it?

Methods

Participants

The research participants were: ten adults without physical impairments (A1-A10), three males and seven females aged from 22 to 38 years (26 ± 4.1); a 10 year 2 month old boy (C1) and a 6 year 10 month old girl (C2) without physical impairments; a 52-year-old female with quadriplegic cerebral palsy (AD1) and a 7 year and 4 month old boy with right side spastic hemiplegic cerebral palsy (CD1). Participant AD1 had great difficulty handling objects and has been classified as level IV in the Gross Motor Function Classification System Expanded and Revised (GMFCS-E&R) (Palisano, Rosenbaum, Bartlett, & Livingston, 2007) and level III in the Manual Ability Classification System (MACS) (Eliasson et al., 2006). AD1 is affected by strabismus and has difficulty focusing on objects with both eyes simultaneously. Participant CD1 has difficulty in reaching out and taking hold of objects with the limb on his affected side. He has been classified as level I in the GMFCS-E&R scale and level III in the MACS scale. CD1 has no visual impairment; however, he was diagnosed with attention-deficit hyperactivity disorder which may cause reduced gaze concentration (i.e., a greater spread of vertical and horizontal eye movements) (Munoz, Armstrong, Hampton, & Moore, 2003). Ethical approval was received from the local Health Research Ethics Board Health Panel at the University of Alberta.

Task

The sorting task in this study was a variation of the dimensional change card-sorting (DCCS) task, which is used to measure self-control and executive functioning in a playful scheme and is suitable for use with children from 3 to 7 years old (Kloo & Perner, 2005; Zelazo, 2006). The standard procedure of the DCCS task is that participants are instructed to sort cards, which differ along attributes (e.g., shape and color), first by one attribute (e.g., by color) in one set of trials, and then by another attribute (e.g., by shape) in the next set of trials. To increase the complexity of the task to try to chal- lenge the adult participants in this study, the figures on the cards varied according to three attributes: color (red, blue, or green), shape (circles, square, or stars), and number of figures (one, two, or three). Plus, for each card, participants were instructed to sort the card according to a randomly generated attribute. See Figure 1 for the cards, pick-up and drop-off locations.

Experimental setup

The system consisted of three components: an eye gaze platform, a haptic robot platform, and a webcam system, as shown in Figure 1. Each component is descried below.

Eye gaze platform

The stationary Tobii eye tracker 4C (Tobii Technology, Danderyd, Sweden) was used as an eye tracking interface. The eye tracker was placed 60 cm away from the participant and connected to a Windows PC and had a sampling fre- quency rate of 90 Hz. The dwell time was set to 1.5 seconds to avoid unintentional selection. When the participant fixated their gaze on one of the three targets in the task environment for 1.5 seconds, the system recognized it as the target that the participant desired to select. If the participant's gaze came off

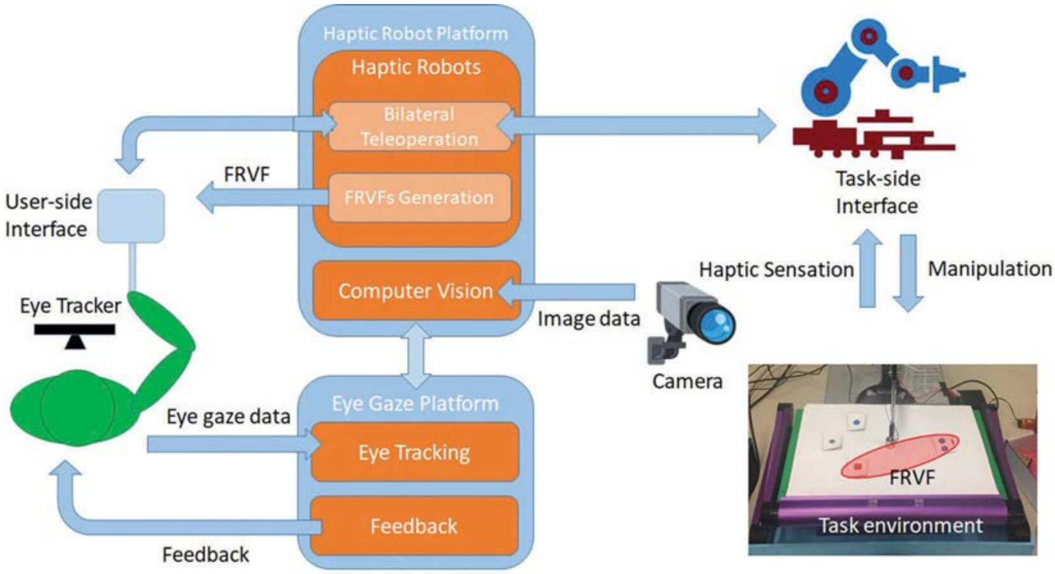

Figure 1. Schematic diagram of the system in interaction with the user and the play environment. The eye gaze platform detects the users' eye movement and provides the feedback when within the target selection radius (i.e., vibrotactile and auditory). The haptic robot platform generates the virtual walls, which only allow the users to move the haptic robot interface inside the walls. The bottom right corner of the figure shows the ellipsoid shaped virtual walls generated between the pick-up point and the selected target point in the task environment (projected onto a 2D plane).

the target before 1.5 seconds was up and then came back on the target, counting of the dwell time started over again.

The eye gaze fixation feedback was given using a USB stereo sound adapter generating a 100 Hz sine wave output. For the auditory feedback, the sine wave was output as sound to earphones that the users wore, and for the vibrotactile feedback, the sine wave was sent to an amplifier to drive a vibration motor (Bit Trade One, Kanagawa, Japan). The motor was attached to the user interface for controlling the robot, so that the motor was in contact with the participant's hand when they were holding the interface. The auditory or vibrotactile feedback (depending on the condition) began when the participant's gaze was within a specified radius from the center point of the target. For the non-disabled adult participants, the radius was set to 3 cm, and for the adult participant with physical impairments and all the child participants, the radius was set to 4.5 cm, chosen based on a pretest to minimize the error of the target selection. The intensity of the feedback increased in proportion to the time the gaze was on the object, as an indication of the progression of the dwell time. The gaze acquisition and the feedback of the eye gaze platform was programed in LabVIEW (National Instruments, Austin, TX, USA). Gaze interaction with no feedback was also tested in the experiments (called no- feedback condition).

Haptics-enabled robotic platform

The robotic platform consisted of two haptics-enabled PHANTOM Premium 1.5A haptic devices (3D Systems, Inc., Rock Hill, SC, USA) programed to be operated synchronously in teleoperation mode (i.e., with a task-side robot following the movements of a joystick interface-like user-side robot). The task-side robot was placed behind the task environment, and the user interface was located beside the participant so they could easily reach it with their hand (Figure 1). An electromagnet was attached on the tip of the end effector of the task-side robot that could be switched ON or OFF to pick up the cards, which were mounted on metallic pieces. The position of the end-effector of the task-side robot was con- trolled and monitored from a program coded in MATLAB/ Simulink (MathWorks, Nadick, MA, USA) and Quarc (Quanser Inc., Markham, ON, Canada).

The virtual walls were generated to restrict the robot end-effector to stay within a desired region depending on the selected target destination. The virtual walls were designed to be an ellipsoid shape generated between the pick-up loca- tion of the card (preset to fixed x, y, and z coordinates) to one of three destination drop-off locations (preset to one of three x, y, and z sets of coordinates) determined by the participant's gaze selection. The ellipsoid-shaped virtual walls were obtained by rotating ellipses about the line joining the pick- up location to the target destination location, and the para- metric equations of an ellipsoid can be expressed as

$$P_{ellipsoid} = \begin{cases} \mathrm{x} = \mathrm{a}\cos\varphi\cos\theta \\ \mathrm{y} = \mathrm{b}\cos\varphi\sin\theta \\ \quad z = \sin\varphi \end{cases} \quad (1)$$

for $\varphi \in [0, 2\pi]$ and $\theta \in [0, \pi]$. Here, a and b are equatoriall semi-major axes of the ellipse along the x-axis and y-axis, respectively. There was no force applied to the haptic end-effector inside the virtual walls, but there were forces applied if the participant tried to move the end effector outside of the ellipsoid region. In other words, when the participant tried to move outside the ellipsoid area it felt like hitting a wall, and the further they pushed the harder the wall felt. Details regarding the implementation of forces are in (Sakamaki, Adams, Gomez, et al., 2017).

Webcam system

A USB webcam (Dynex, Richfield, MN, USA) was mounted over the task environment, which acquired the image data of the entire area of the environment. This image data was processed to obtain the position data of the targets and the card located in the task environment.

Accurate position control of the teleoperated robots required the use of a homogeneous transformation that was calculated from three separate position frames: the eye tracker frame, webcam frame, and robot frame, shown in Figure 2. The relationship between the position of the robot end-effector and a corresponding position of the eye gaze with respect to the fixed camera can be represented by a 4 × 4 homogeneous matrix T. This can be written as

$$^{C}P = {}^{C}_{E}T\,^{E}P \tag{2}$$

$$^{R}P = {}^{R}_{C}T\,^{C}P \tag{3}$$

where ^{E}P ^{C}P, and ^{R}P denote three different augmented vector presentations of an arbitrarily chosen point represented in the eye tracker frame, camera frame, and robot frame, respectively. The ${}^{C}_{E}T$ and ${}^{R}_{C}T$ denote the transformation between the eye tracker and the camera frame, and the camera and the robot frame, respectively (Craig, 2005). Note that since the camera and the eye tracker could only acquire the points in 2-dimensional space, values on the y axis were set to a constant value that corresponded with the ground plane coordinates of the robot's position.

Procedures

The participant performed 12 trials of the card sorting in each of four task conditions: virtual wall off, i.e., no target selected with eye gaze and just free movement of the robot end- effector (FRVF-off), virtual wall on after selecting target with no eye gaze feedback (FRVF-on with no feedback), virtual wall on after selecting target with auditory feedback (FRVF-on with auditory feedback), and virtual wall on after selecting target with vibrotactile feedback (FRVF-on with vibrotactile feedback). The order of the task conditions was randomly assigned. The FRVF-off condition was used as a baseline of the participant's task performance without any assistance from the FRVF.

At the beginning of the session, the position of the user interface was adjusted until the participant indicated they felt comfortable moving it with their non-dominant hand for the adults without impairments and their dominant hand for the children without impairments. The adult and child with impairments were using their affected hand. The robot frame and the eye tracker frame were mapped to the camera frame of the task environment using the homogeneous transformation. In each trial the researcher placed a card on the pick-up location and the participant was asked to sort the cards with the robot system. A verbal instruction was given by compu- ter about what attribute to sort on. In the FRVF-off condi- tion the participant could move freely to sort the objects. The participant started with the robot end-effector at the start location and moved to the card pick-up location. When the robot end-effector reached the pick-up location, the electromagnet attached on the tip of the end-effector was automatically activated, and the metallic card was "picked up". When the robot end-effector reached the target destina- tion location, the magnet automatically released the card from the end effector. In the FRVF-on conditions, the parti- cipant first fixated their gaze at the desired target destination (while receiving no, auditory or vibrotactile feedback). When the system determined that the participant's gaze was on a target, a computerized voice confirmation was given to the participant (e.g., "target A was selected"). The virtual walls were activated between the pick-up and the selected target locations, and the participant could move the robot end effector along the ellipsoid-shaped virtual walls to the target destination.

At the end of the session participants were asked about their preferred feedback modality for selecting targets with eye gaze and if they felt that the virtual walls were helpful to move the robot to the target location.

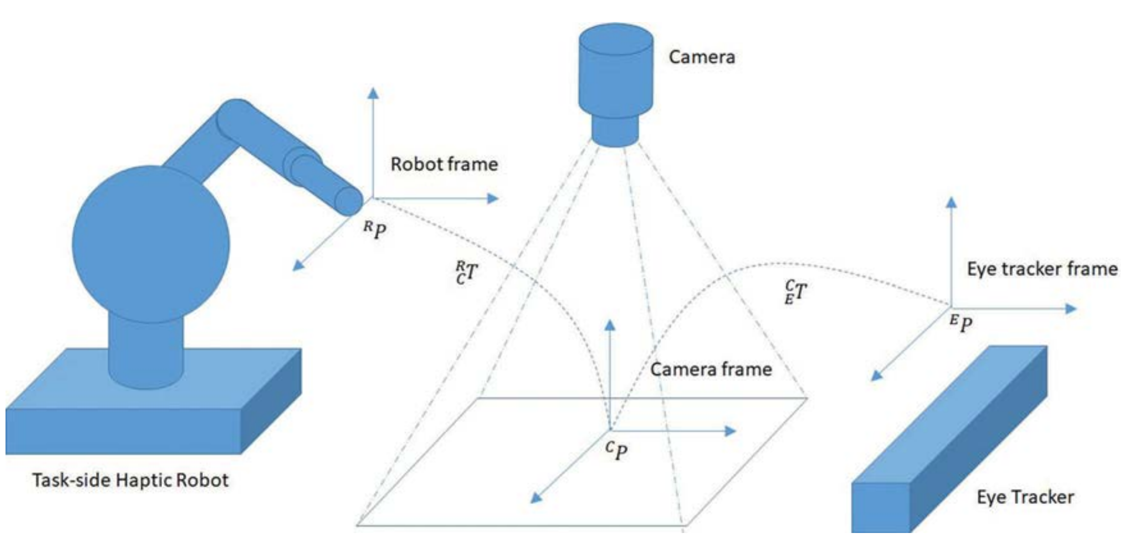

Figure 2. Homogeneous transformations, that is, a reprojection between a point in the robot frame, the camera frame, and the eye tracker frame.

Measurements and analysis

The following variables were measured and analyzed for each trial:

- Target Selection Time: The time from when the system gave the verbal instruction about what attribute to sort on until the target was selected by eye gaze fixation. A trial timed out and moved to the next trial if a participant could not select the target within 10 seconds,
- Robot Travel Time: The time from when the card was picked up until it was released on the target location,
- Robot Trajectory Length: The distance of the traveled path of the robot end-effector from the pick-up location to the target destination location.

Correct Card Sorting Rate was calculated for each task condition as the percentage of the number of cards that were sorted correctly divided by the total number of cards sorted in that condition.

Statistical analysis was conducted on the data of the ten non-disabled adult participants (A1-A10). The Shapiro-Wilk normality test was performed first to check if the data was normally distributed. If the normal distribution of the data was confirmed, the target selection time was entered into an analysis of variance (ANOVA) with a factor of the feedback modality for the gaze fixation (3 levels: FRVF-on with no- feedback, FRVF-on with auditory feedback, and FRVF-on with vibrotactile feedback). Additionally, the robot travel time, the robot trajectory length, and the correct card sorting rate were compared using an ANOVA with a factor of the task condition of the experiment (4 levels: FRVF-off, FRVF- on with no-feedback, FRVF-on with auditory feedback, and FRVF-on with vibrotactile feedback). In all cases, a probability of $p < .05$ was considered significant. If the data was not normally distributed, a pair-wise permutation test was used for the analysis. Descriptive analysis of the data from the other participants were performed individually because of the low sample size.

The Percentage of Difference for the target selection time, robot travel time, and robot trajectory length were calculated to express an increase or decrease of the data from the base- line conditions (i.e., the FRVF-on with no-feedback condition was the baseline for target selection time, and the FRVF-off condition was the baseline for the robot travel time and the robot trajectory length). All the correct and incorrect card sorting trials were included for the analysis. Choices and comments about eye gaze feedback preferences and helpful- ness of the virtual walls were tabulated.

Results

The mean target selection time of the 12 trials in each task condition for the different eye gaze feedback modalities is shown in Figure 3. No statistical significant difference was found in the data for the ten non-disabled adult participants ($F[2,18] = 0.23$, $p = .7927$). Table 1 shows the percentage of difference in the target selection time of the auditory and vibrotactile feedback from the no-feedback condition for the other participants. The data of 2 trials from C1, 4 trials from C2, 6 trials from AD1, and 5 trials from CD1 were excluded due to the timeout error in target selection.

Figure 4(a) shows the average robot travel time of the 12 trials in each task condition for all the participants. From the figure, the time for the FRVF-off condition appears to be shorter than all the FRVF-on conditions for the ten non-disabled adult participants, and performing the ANOVA for a statistical analysis, a significant difference was found ($F [3,27] = 3.619$, $p = .0256$). The post hoc tukey's HSD test showed a significant difference in the robot travel time between the FRVF-off and the FRVF-on with no-feedback condition. Table 2 shows the percentage difference in the robot travel time after selecting targets using the different feedback modalities for the other participants.

Figure 4(b) shows the average of the robot trajectory lengths of the 12 trials in each task condition. There was no significant difference in the robot trajectory length between the different task conditions for the ten non-disabled adult participants ($F = [3,27] = 2.44$, $p = .0857$). Table 2 shows the percentage of difference between the FRVF-on conditions after selecting tar- gets using the different feedback modalities and the FRVF-off condition for the other participants. Figure 5 illustrates the robot

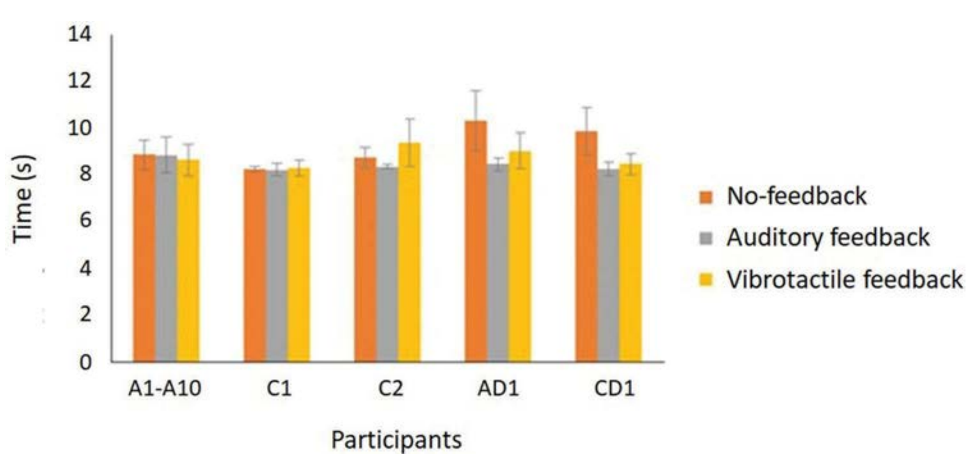

Figure 3. Target selection time with the different feedback modalities for the ten non-disabled adult participants, the participant. C1, C2, AD1, and CD1.

Table 1. Percentage of difference in the target selection time of the feedback modalities from the no-feedback condition for all the participants.

	Percentage of difference (%)	
	Auditory	Vibrotactile
C1	−0.3	0.71
C2	−4.51	7.04
AD1	−17.56	−12.55
CD1	−16.56	−14.4

trajectories during the entire task of each condition for on adult, the one whose robot trajectory length was closest to the average among the non-disabled adult participants, and the other participants.

The correct card sorting rates for all the participants are summarized in Table 3. No trend difference between correct and incorrect sorting trials was observed in any of the outcome variables.

Discussion

In this study, we developed an eye gaze controlled haptic robot platform to guide the user with virtual walls toward the desired target locations. The purpose was to have a system that did not require a computer screen for the feedback about eye gaze fixation location, so alternative feedback modalities were tested, and the usefulness of the virtual walls was exam- ined. The system was feasible, in that the virtual walls were successfully generated based on eye gaze data in real time in this sorting task. We expected that some feedback about eye gaze location would be better than not having any feedback, which was not the case for the adults without impairment, but was the case for the youngest child and the individuals with physical impairment. This may be because the 3 cm acceptance size for the gaze fixation was large enough for the adults without physical impairment to easily select the target. The performance of the child participant without physical impairments, C1, was similar to the results of the adults, having no difficulty performing gaze fixation even with no feedback. C1 was 10 years old, and appears to have mature eye gaze behavior. The target selection time for the 6 year old child participant without physical impairment, C2, differed among the feedback modalities with vibrotactile feedback being clearly longer than the no-feedback condition. The performance of the target selection for the adult participant with physical impairments, AD1, and the child participant with physical impairment, CD1, were similar to each other. The no- feedback modality took more time to select the target, mean- ing that the feedback must have been helping them sustain their gaze on the target. The difference in target selection time between auditory feedback and vibrotactile feedback were smaller compared to the difference between the no-feedback and these feedback modalities. Our findings about any feed- back being better than no feedback for the case studies, and there being little difference between visual and auditory feed- back, are similar to findings of Rantala et al. (2017). They reported that feedback has been found to improve perfor- mance in gaze interaction, however, all the modalities gener- ally perform equally. Thus, the choice of which feedback to use, could be determined by user preference.

According to the participants comments, seven out of 10 participants said they preferred the vibrotactile feedback for the target selection with eye gaze because their hand was already in place to subsequently operate the robot, so sensing the vibration at the interface they were holding was easier and more intuitive than the auditory feedback. One participant commented that auditory feedback was sometimes distracting and made it more difficult to hear the task instructions.

Even with feedback, selection of targets with the eye gaze was not always successful for the case study participants. The adult and the child with physical impairment had timeout errors in 6 and 5 trials out of 36, respectively. This means that they were not always able to sustain their gaze within the 4.5 cm radius of the target location for the full 1.5 second dwell time to complete the selection before the timeout

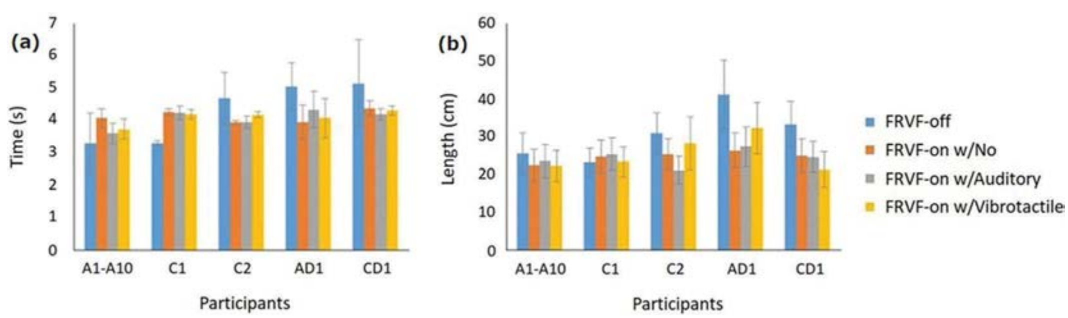

Figure 4. (a) Robot travel time and (b) Robot trajectory length with the different task conditions for the ten non-disabled adult participants, the participant.C1, C2, AD1, and CD1.

Table 2. Percentage of difference in the robot travel time and robot trajectory length of the FRVF-on conditions from the FRVF-off condition for all the participants.

	Robot travel time			Robot trajectory length		
	FRVF-on (no-feedback)	FRVF-on (Auditory)	FRVF-on (Vibrotactile)	FRVF-on (no-feedback)	FRVF-on (Auditory)	FRVF-on (Vibrotactile)
C1	29.48	29.18	27.66	6.63	9.67	1.33
C2	−15.78	−15.66	−10.75	−17.52	−31.25	−8.23
AD1	−21.67	−14.06	−19.35	−35.94	−33.47	−21.62
CD1	−15.05	−18.45	−16.33	−24.65	−25.79	−35.56

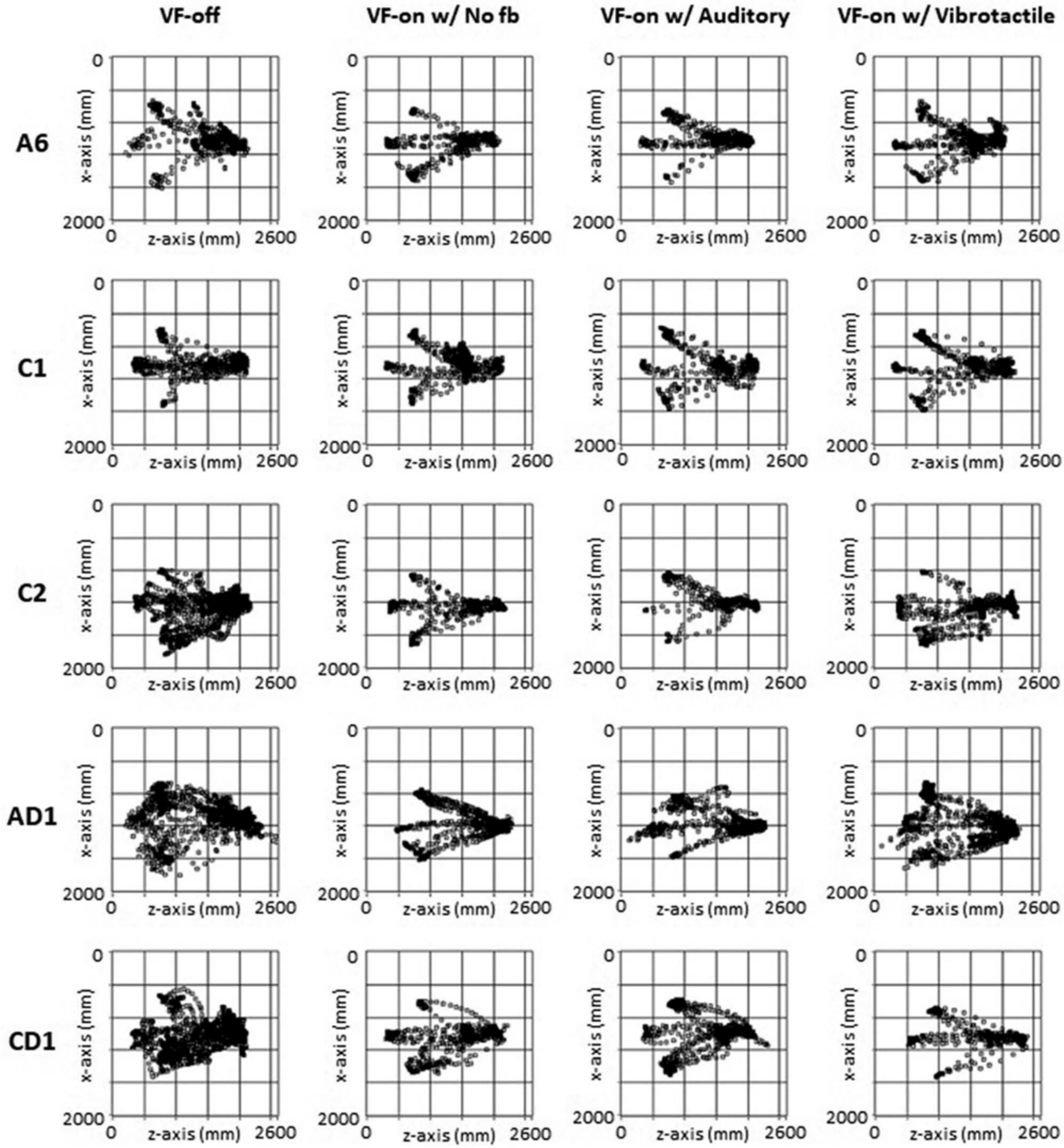

Figure 5. Robot trajectories for one of the non-disabled adult participants (A6), the participant C1, C2, AD1, and CD1 during: FVRVF-off, FRVF-on with no-feedback, FRVF-on with auditory feedback, and FRVF-on with vibrotactile feedback.

Table 3. Correct card sorting rate in the different task conditions for all the participants.

	Correct card sorting rate (%)				
	A1-A10	C1	C2	AD1	CD1
FRVF-off	100	100	91.67	100	75
FRVF-on w/No-feedback	100	100	50	100	84.62
FRVF-on w/Auditory	100	100	66.67	100	66.67
FRVF-on w/Vibrotactile	100	100	58.33	100	54.55
Average	100	100	67	100	70

occurred (10 second timeout window). Their impairments, i.e., the spasticity and strabismus for AD1 and the attention- deficit hyperactivity disorder for CD1, may have made it difficult for them to keep their heads still and accurately fixate their eye gaze for target selection. The participant AD1, CD1, and the 6 year old child participant C2, had trouble staying still during the tasks, and the system needed to be recalibrated several times during the experiments. Increasing the accep- tance size could help make target selection easier; however, this would result in fewer targets allowed in the environment. Instead of simply increasing the target acceptance size, applying machine learning techniques for the system to adapt to each individual's gaze behavior could improve the success rate of the target selection for these populations. Or, alternate eye gaze hardware could be used. The stationary eye tracker in this study allowed lower cost, but it may not be appropriate for situations where the users are not able to stay still and fixate their eye gaze within the required range. Replacing the stationary eye tracker with a head-mounted eye tracker would help attain stable gaze acquisition and give more freedom for users to move more naturally during the tasks, as long as the users could tolerate wearing one.

For robot operation performance, the conditions with virtual walls-on had longer travel times for the non-disabled adults compared to the virtual walls-off condition. This is contrary to our expectation, but likely caused because the participants tended to follow along the boundary of the FRVF and explore it when it was on, which was a detour from a straight line between the pick-up location and the target location. There were also longer travel times with virtual walls-on for 10-year-old non-disabled child partici- pant, C1. One can see in Figure 5 that the adults and C1 were quite efficient in their robot trajectories even when the virtual walls were off. On the other hand, the virtual walls made the travel time shorter for the 6-year-old child partici- pant without disabilities, C2, the adult participant with phy- sical impairment, AD1, and the child participant with physical impairment, CD1.

Likewise, the robot trajectory length with virtual walls-on was expected to be shorter than the virtual walls off conditions because for the former, the participant's trajectory is constricted to prevent unnecessary robot travel. This was not the case for the adult participants without physical impairment, nor the 10 year old child participant without physical impair- ments, C1. However, the trajectories without virtual walls of the 6 year old non-disabled child participant C2 and the adult and child with physical impairments, AD1 and CD1, were more spread out, and at least 20% longer than the conditions with virtual walls. Thus, the participants with physical impairment and the youngest child participant, whose motor skills were less developed than the adult participants and 10 year old child without disabilities, benefited from the virtual walls as far as time and trajectory efficiency of the robot movement.

All the participants commented that the virtual walls were helpful to accomplish the card sorting task by showing the correct direction to move their hand. Even the adults and the child without physical impairments indicated that the task was easier with the virtual walls, It is interesting that they still felt that the virtual walls were helpful even though the walls did not improve their robot travel time or trajectory length.

Even with the variation on the DCCS card sorting task to make it more complex, none of the adult participants made mistakes, nor did the 10 year old without physical impairments, C1. However, their participation helped to test the feasibility of generating virtual walls in real time. The 6 year old child participant with physical impairment, C2, and the 7 year old child participant with physical impairment, CD1, are in the target age for the DCCS task, thus variation in their performance was expected. Interestingly, C2 achieved 91.67% correct card sorting rate in the condition without virtual walls, but the correct card sorting rates decreased to between 50 to 66% in the conditions with virtual walls. Having to fixate her gaze on the target location to generate the virtual walls before doing the card sorting may have increased the task complexity and affected her performance. More research is needed with children to investigate how to reduce the cognitive load of using a system such as this.

This study had some limitations yet to be mentioned. First, due to the small sample size of the participants with physical impairment, the findings in this study can serve only as preliminary data guide further research. Second, the timeout errors for the adult and child with physical impairments and children without physical impairments reduced the data set, though no statistical tests were applied. Third, the time between finishing selecting the target with eye gaze and before starting to move the robot to the pick-up location was not recorded. This time could be an indication of the cognitive load of experiencing the different feedback systems for eye gaze feedback, and should be measured in future studies.

Conclusion

The haptic robot platform was capable of generating virtual walls in real time based on eye gaze fixation of targets in the physical environment in this sorting task. It was validated with adults without disability, and then the behavior of the system was examined in case studies with children and indi- viduals with physical impairment. A benefit of the system was that it does not require a computer in the environment to receive feedback about eye gaze fixation location. The feed- back about eye gaze fixation did not improve the selection time of the adults without physical impairment, but did help to improve selection time for the individuals in the case studies. Performance with the auditory and vibrotactile feed- back was equivalent, but the participants had a preference for the latter. They appreciated that the feedback is incorporated into the interface, and could be beneficial in future studies. The virtual walls were able to restrict the users' hand move- ment inside a defined region, and though it did not reduce the time and distance of trajectory of the robot movement in the feasibility tests with the adults without physical impairment, it did for the adult and child with physical impairment. From this perspective, the system allowed the users with physical impairment to have more efficiency interacting with the physical environment. Another contribution of this study was that even if the participants made a mistake on the card sorting task, the system generated virtual walls toward the target location the participants chose, even if it was a mistake, which enables assessment of their skills, and allows them to learn from their mistakes. The system in (Sakamaki, Adams, Gomez, et al., 2017), where object recognition by computer vision always generated the virtual walls to the correct location, could have a role when wanting to ensure children have success at tasks. The system developed in this study can be used for situations such as games with scores or assessments to test cognitive skill levels. Finally, since the target locations are based on a homogenous transformation and generating virtual fixtures based on eye gaze fixations in real time, it is flexible for use in other pick and place tasks. Next steps are further development of the system, and testing with more participants with physical impairment.

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Disclosure statement

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