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Preliminary testing by adults of a haptics-assisted robot platform designed for children with physical impairments to access play

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Abstract

Development of children's cognitive and perceptual skills depends heavily on object exploration and experience in their physical world. For children who have severe physical impairments, one of the biggest concerns is the loss of opportunities for meaningful play with objects, including physical contact and manipulation. Assistive robots can enable children to perform object manipulation through the control of simple interfaces. Touch sensations conveyed through haptic interfaces in the form of force reflection or force assistance can help a child to sense the environment and to control a robot. A robotic system with forbidden region virtual fixtures (VFs) was tested in an object sorting task. Three sorting tasks—by color, by shape, and by both color and shape—were performed by 10 adults without disability and one adult with cerebral palsy. Tasks performed with VFs were accomplished faster than tasks performed without VFs, and deviations of the motion area were smaller with VFs than without VFs. For the participant with physical impairments, two out of three tasks were slower with the VFs. This implies that forbidden region VFs are not always able to improve user task performance. Alignment with an individual's unique motion characteristics can improve VF assistance.

Keywords: haptics, virtual fixtures, robot, vision, people with disabilities, object manipulation.

Play is an enjoyable and natural way for children to develop self-expression and social abilities. Play involves discovery, learning, mastery, creativity, and adaptation (1). Through play, children explore the relationship between their bodies and the environment using sensory information; they gain information about object properties and develop rules about their own temporal and spatial locations (2). Children with physical disabilities often have difficulty interacting with the environment and manipulating objects. This can cause developmental delays and isolation from the social environment, and hinders linguistic, social, and cognitive development (3, 4). When children are not able to manipulate objects independently, they may be perceived as being more developmentally delayed than they are (5, 6).

Robotic systems can help children with disabilities learn skills through play (5). Robots such as the Play-ROB (7, 8) and the Lego robots (9) enable children with cognitive and physical disabilities to manipulate objects. Interfaces for these robots are, respectively, a joystick (7, 8) or switches (9). These interfaces do not give feedback to the user about object properties. Users gain more flexibility with joysticks than switches, but children with physical impairments may not be able to manipulate joysticks appropriately.

Haptic interfaces generate kinesthetic touch sensations by conveying forces, vibrations, or motions to the user (10, 11) and can therefore enhance a child's exploration of the environment (12). Robotic systems with haptic feedback capability can be applied in cooperative manipulation, where a human holds the haptics-enabled robot and manipulates objects directly, and in telemanipulation, where a human operates a robot (user-side device) that controls another robot that performs a task (task-side device) (13). Cooperative manipulation is intuitive as the user applies natural hand-eye coordination, whereas telemanipulation has the benefit of remote operation, and position/force scaling and movement adjustments can be applied at the task-side device.

A haptic telerobotics platform to enhance task performance was tested by an adult with cerebral palsy (CP) in a physical play environment (14). The haptic capabilities of the system allowed forces occurring at the task-side robot to be felt at the user-side robot, and the system also scaled up the user's limited range of motion and made the user's movements smoother. The involuntary component of the hand motion, which has a high-frequency in comparison with the voluntary component of the hand motion, was filtered out. Plus, movements that passed through the filter were dampened by a factor that the user chose as comfortable. This platform enabled the individual with CP to accurately perform a sorting task requiring large-scale motions.

Haptic interfaces can create virtual fixtures (VFs); these are software-generated forces applied by the robotic interface (13). Guidance VFs assist in guiding the robot along a desired area, while forbidden region VFs help to keep the robot inside (or outside) a defined region.

Vision-motion integration (15) is often used in automated manufacturing lines, in robotic systems that perform visual inspection, in pass/fail decisions, and in object handling in industry. Sharari (16) developed a vision-based robotic system with a five degree of freedom robotic arm that discriminates objects by color and shape, and places the object in the corresponding target location. Bettini, Marayong (17) designed a system with VFs determined by computer vision. A combination of various VF shapes (i.e., straight lines, curved lines, tube-shaped cylinders, or cone-shaped funnels) helped the user move between an object and a target destination smoothly and accurately.

Sorting and classifying are fundamental concepts that help children to gain an ability to differentiate between objects according to their characteristics such as size or color. It encourages the development of logical thinking about objects, events, number sense and early counting skills (18). Children with physical impairments may have the cognitive abilities to understand sorting but might have trouble manipulating the objects and moving them to target locations. As a first step in developing a robotic system for children's play and development, a system with VFs that help a user move an object toward an intended location could assist the sorting efforts of a child with disabilities.

This paper examines if a cooperative manipulation robotic system with a forbidden region VF, determined by computer vision, is helpful in completing a set of sorting tasks more accurately, quickly, and with higher movement efficiency. The research question was: Can forbidden-region VFs improve the (a) success rate, (b) completion time, and (c) area of movement in a sorting task?

1. Methods

The intended target population will be children who have physical impairments, but this preliminary study was done with adults without disability and an adult with physical disabilities. This was because the system was in the preliminary testing stage and still required careful validation of accessibility and safety before being used by our target population. The study was designed to examine if the performance of an individual with disabilities confirmed the results of trials with individuals without disability. The study allowed us to explore potential problems early in the developmental stage and give experiential knowledge for future studies (19). A method was used for participants without disability to simulate having a movement disability: they used their nondominant hand to operate the robot and viewed the play environment through a head-mounted display that randomly changed the orientation of the view for visual confusion (described in more detail later). Use of the non-dominant hand and visual confusion were employed to encourage movements not aimed directly at the target position, thus engaging the system's VFs. Simulation of impairments by participants without disability has been reported in previous studies, for example in access to augmentative communication devices (20) and access to computers (19). In future studies with children with disabilities, they will use their dominant hand and there will be no visual confusion.

The repeated measure cross-over design involved adult participants without disability and an adult participant with physical impairments. The study was approved by the Health Research Ethics Board at the <to be inserted after blind review>.

1.1. Participants

Ten university students without disability, three males and seven females, aged from 22 to 32 (27 ±3.6), with no previous experience manipulating haptic robots participated in the study.

The system was also tested by < author # to be inserted after blind review>, an individual who has quadriplegic cerebral palsy and is 48 year old female. She has mixed high and low muscle tone and involuntary movements. She has been classified as Level IV in the Gross Motor Function Classification System Expanded and Revised (GMFCS-E&R) (21), and Level III according to the Manual Ability Classification System (MACS) (22). This classification means that she performs self-mobility by using a powered wheelchair, and has difficulty handling objects.

1.2. Materials

The sorting task was a variation of the dimensional change card-sorting (DCCS) task which is administered in a playful scheme to assess and measure self-control and executive functions; the DCCS is suitable for use for children from 3 to 7 years old (23, 24). The DCCS was chosen as the first step in our research because it had a well-defined protocol aimed at our target population age.

The DCCS protocol allows for substitution of other objects instead of cards, and we used red and blue circle or square tokens varying by different dimensions, i.e., color, shape, or both.

The robotic system consisted of a main system and a subsystem. The main system controlled the robot and included a Windows PC, a Microsoft Kinect (Microsoft Co., Redmond, WA, U.S.), and a PHANTOM Premium 1.5A haptic device (3D Systems, Inc., Rock Hill, SC, U.S.) working as a cooperative manipulator. The Kinect was mounted above a physical play environment for vision-based object detection. The subsystem for visual confusion included another Windows PC, a USB webcam, and a Google Cardboard Viewer (Google Inc., Mountain View, CA, U.S.) with an Apple iPhone (Apple Inc., Cupertino, CA, U.S.) as a head-mounted display. The webcam was mounted beside the Kinect. The image from the webcam was displayed on the head-mounted display and was changed as described in procedures. A physical play environment was placed in front of the haptic device and a Lego platform enabled the placement of objects needed, such as a pick-up location for tokens and two destination containers in the diagonal position, one to the upper left side and one to the lower right side of the pick-up location, which required the participants to move proximally and distally as well as left or right rather than just left or right in a parallel line. The participant held the end-effector of the haptic device to manipulate the tokens. A magnet was attached to the tip of the end effector to pick up the tokens, which each contained a piece of metal. A picture of the system and a schematic diagram are shown in Figure 1, and the view of the play environment through the head mounted display are shown in Figure 2.

----- Insert Figure 1 about here-----
----- Insert Figure 2 about here-----

The software used for this project were Release 2011b of Matlab/Simulink (MathWorks Inc., Nadick, MA, U.S.) and Quarc V2.2 (Quanser Inc., Markham, ON, Canada). Quarc is a software library that provides Simulink blocks for accessing external robotic devices, including the PHANTOM Premium. In addition, System Control Toolbox, Image Acquisition Toolbox, Computer Vision Toolbox, and Image Processing Toolbox were used as Matlab add-ons.

Object Recognition

A token placed in the play environment was image-captured by the Kinect, and its color and shape were detected by object recognition functions coded in Matlab/Simulink. At first, an RGB filter operation was performed. The range of the RGB operation values were $15 \leq R \leq 256\ AND\ 186 \leq G \leq 256\ AND\ 0 \leq B \leq 202$. This operation filtered out any objects that were not red or blue in color in the image frame. When the system detected either a red or blue object in the frame, it proceeded to the next step, which was color/shape recognition. For color recognition, the RGB values at the centroid of the object were detected. The color classification was achieved based on thresholds as follows:

Red: $166 \leq R \leq 256\ AND\ 0 \leq G \leq 256\ AND\ 0 \leq B \leq 115$
Blue: $0 \leq R \leq 77\ AND\ 0 \leq G \leq 256\ AND 166 \leq B \leq 256$

For shape recognition, the roundness of the object was computed with the following formula:

$$Roundness = \frac{4\pi \times Area\ of\ Object}{Perimeter\ of\ Object^2} \tag{1}$$

The value of roundness gives an indication of how close the object is to a circular shape. A perfectly shaped circle has a roundness value of 1. If the object is far from a circular shape, the roundness value is much less than 1. The values for *Area of Object* and *Perimeter of Object* in the equation above can be computed by the Matlab Image Processing Toolbox. The roundness threshold level was set to 0.87 based on manual tuning prior to the study, therefore, tokens having roundness values greater than or equal to 0.87 were classified as circle objects and tokens having roundness values less than 0.87 were classified as quadrilateral objects.

Virtual Fixtures

VFs were added to the system as software-generated forces. The desired region of motion was defined by a closed horizontal cylinder along the desired area, connecting a pick-up point (preset to fixed X, Y, and Z coordinates) to one of two destination points (preset to one of two X, Y, and Z sets of coordinates). The destination point was where the object was meant to be placed by the user and was determined based on the color or shape of the target object. Once the destination point was determined, VF forces (F_{VF}) were generated to create the cylinder-shaped VFs. There was no force applied to the haptic end-effector inside the cylindrical area, but there were forces applied if the user tried to move outside of the area. A VF was implemented as a nonlinear spring force attached between the current position of the robot's end-effector ($P_{end\,effector}$) and a reference point ($P_{reference}$) at each instant. The reference point was determined by the perpendicular projection of $P_{end\,effector}$ onto the line joining the pick-up point to the destination point (Figure 3). At each instant, the distance between $P_{end\,effector}$ and $P_{reference}$ was calculated and compared with the radius of the cylinder. The radius of the cylinder was set to 0.01 m. If the measured distance was greater than the cylinder radius F_{VF} was applied to the robot based on the following formula:

$$F_{VF} = \begin{cases} k * |distance|^3, & if\ distance > radius \\ 0 & , else \end{cases} \tag{2}$$

$$where:\ k = spring\ constant, \qquad distance = P_{reference} - P_{end\,effector}$$

The spring constant determined the amount of force applied; the larger the *k* value, the stiffer the boundaries of the cylinder. The *k* value was set to 1 N/m. The forces were scaled up in a cubic relationship so that the user would feel a small force when coming into contact with the boundaries and a much greater force if pushing further against the boundaries. The direction of F_{VF} was determined by the sign of the distance, i.e., toward the reference point in order to push the user's movements away from the boundaries.

----- Insert Figure 3 about here-----

1.3. Procedure

Participants performed three sorting tasks with the VF settings off and on (VF_{off} and VF_{on}). All the participants were asked to sit and grasp the robot end effector and reach for the two destination containers before their trials, so that they could find in a comfortable position for the sorting tasks. The nondominant hand was used to operate the robot for participants without disability while the dominant hand was used for the individual with disabilities. As mentioned above, this was done to make the tasks more difficult for adults without disability and to engage the VF during the tasks.

The participants without disability only viewed the play environment through a head-mounted display that randomly changed the orientation of the view for visual confusion. The image of the play environment was changed from upright to upside down, inverted sideways, and inclined 45 and 135 degrees randomly (See Figure 2). As described above, visual confusion was employed to encourage movements not aimed directly at the target position, thus engaging the system's VFs. The individual with physical impairments looked directly at the play area and used her dominant hand to operate the robot.

The first two sorting tasks were one-dimensional (i.e., color or shape) and the third task was two-dimensional (i.e., color and shape; herein, color-shape). The order was the same for all participants with and without disabilities: color, shape, color-shape. The first setting of the VF was randomly assigned, ensuring counterbalance, i.e., five participants started with VF_{off} and five started with VF_{on}.

For the color and shape sorting tasks, there were six tokens, three red circles and three blue squares, presented in quasirandom order, that is, no more than two tokens of the same color (or shape) appeared consecutively. The target locations (i.e., whether the red should go to the left or the right of the pick-up location) were switched randomly and to indicate the target location a blue circle and a red square token were placed next to the target boxes; target locations on the same side appeared no more than twice in a row. This differed from the DCCS protocol, but was implemented to increase the complexity of the task, so that participants could not rely on memory that a color always went to the same side. However, sometimes this resulted in an uneven number of tokens in the target containers.

For the color-shape task, there were 12 tokens, three red circles, three blue circles, three red squares, and three blue squares. The target locations were fixed (no switching); all red tokens and square tokens went in one container and blue tokens and circle tokens to the other. The participant was instructed to sort the token according to a certain attribute, e.g., “sort by color” or “sort by shape,” then the token was placed on the pick-up location. Participants were not told about the VF feature until the end of the session.

At the end of the session, VFs and their function were explained, and participants were asked to answer a question about the ease of the tasks and to state their opinion on scale of one to five (1 = *strongly disagree* and 5 = *strongly agree*) regarding several aspects of the tasks. The question and statements are shown in column one of Table 1. The participants were also asked if they had any comments to add.

--- Insert Table 1 about here ---

1.4. Data collection and analysis

All sessions were videotaped and reviewed by two research assistants to measure success rates and completion times of the sorting tasks. The success rate was equal to the percentage of the number of tokens that were placed in the correct container divided by the total number of tokens in each task. The completion time was equal to the time taken by a participant to sort a token (from the pick-up point to the target location). The average time to sort a token within each task was calculated (e.g., the average over six tokens for the color and shape tasks, and over 12 tokens for the color-shape task). The reliability of the success rate and the completion time were examined by observation of 20% of the participant videos by a second reviewer and calculated using the Interclass

Correlation Coefficients (ICC). Excellent reliability values in the success rate (ICC = 1.0) and the completion time (ICC = 0.984) were obtained.

The motion trajectory of the end-effector was recorded for the last seven participants and the participant with physical impairments at a sampling frequency of 1 kHz. The trajectory data were saved in X, Y, and Z directions; however, since the tasks were two-dimensional, the trajectory analysis was performed with only X and Y data, with Z data equal to zero. The area of movement was calculated as the bounded area of the trajectory in square meters. It was measured by the Matlab function, *boundary(X, Y)*, where X and Y correspond to a vector of sample points on the trajectory. This function returns a vector of point indices representing a single conforming 2-D boundary around the sample points and the area of that movement.

Multiple paired comparisons with a 95% confidence level were made to analyse the effect of the VFs on completion time and area of movement within each task by using a paired-samples t-test when the normality assumption was met and the Wilcoxon signed-rank test when it was not. Success rate, completion time, area of movement, and questionnaire responses for participants without disability were compared with those rendered by the participant with physical impairments.

The responses to the qualitative question were tabulated, and the mode and range of the ratings to the statements was calculated. Related comments were transcribed.

2. Results

The tokens used for the color and shape tasks were mistakenly three blue circles and three red squares instead of three red circles and three blue squares. A blue circle and a red square were used as target indicators for eight of the participants without disability, thus, the target indicators did not include a change of dimension from color to shape. This mistake should have made it easier for the participants to sort them, but four out of the eight participants for which this situation happened made mistakes when sorting the tokens with VF_{off}. Therefore, it was decided to use the data. For VF_{off}, the average success rate over all participants without disability for the color task was 91.7% with a range of 50–100%, for the shape task the average was 98.3% with a range of 83.3–100%, and for the color-shape task the average was 98.2% with a range of 91.7–100%. The success rate for the three tasks with VF_{on} was 100% for all tasks. The participant with physical impairments performed all the sorting tasks with a success rate of 100%.

Table 2 shows the means and standard deviations of the completion time and area of movement values for each task with VF_{off} and VF_{on}. The within-group comparisons for the participants without disability between VF_{on} and VF_{off} that revealed significant differences are marked with an asterisk. The completion time for the color-shape task was significantly longer with VF_{off} than with VF_{on} ($p = 0.011$). All area of movement values were significantly higher with VF_{off} than with VF_{on} (color $p = 0.018$, shape $p = 0.019$, color-shape $p = 0.018$). Details from the t-test and the Wilcoxon test are shown in Supplementary file 1. Table 2 also shows the sorting values for the individual with physical impairments.

--- Insert Table 2 about here ---

Figure 4 illustrates trajectories for VF_{off} and VF_{on} for the participant whose area of movement was closest to the average for VF_{off} in the color-shape task. For the participant with physical impairments, the trajectories for all tasks are shown in Figure 5.

----- Insert Figure 4 about here-----
----- Insert Figure 5 about here-----

Table 1 shows the range and mode of responses to the questions and statements for the participants without disability and the individual with physical impairments. There was a large range in responses. However, the comments of the participants without disability indicated that the VFs were helping them to accomplish the task by giving the correct direction to move their hands, and that with no VFs it was harder to move their hand from one point to another point. One participant referred to the VFs as a "resistance" that was hard to handle at the beginning, but that eventually helped him to complete the task successfully. Some participants said they learned how to do the movements because they performed the movements several times. Participant comments about statement b in Table 1 were that the VFs gave them a physical orientation to the target destination, correcting them when they were wrong, and indicated when they should stop moving. One participant mentioned that he felt he accomplished the tasks faster with VF_{on}.

Comments about statement c in Table 1 revealed that low participant ratings were based on the instability and vibration the robot exhibited when they tried to go beyond the end of the cylindrical shaped area at pick-up and target locations in the VF_{on} mode. The participant with physical impairments commented that her involuntary movements were fighting against the boundary of the area created by the VF. For statement e in Table 1, some participants said they memorized the movements to get to each target box and did not rely on the video in the head-mounted display. An additional comment was made regarding the shape of the VFs. One participant did not feel comfortable with the straight cylindrical shape because he wanted to move toward the target along an arc pathway whereas the VFs made him to go in a straight line between pick-up and target locations.

3. Discussion

The tasks with VF_{on} for both participants without disability and the participant with physical impairments achieved a success rate of 100%. This indicates that object recognition and VF generation for the system worked properly during the sessions. The overall success rate for VF_{off} was 96%. Because the participants were adults who have had experience with sorting skills since childhood, we expected their sorting result to be 100% accurate. The visual confusion engendered by the head-mounted display that randomly changed the orientation of the view must have elicited some confusion about the dimension they were sorting. In the future, when children do this study, we expect success rates with VF_{off} to be lower, especially for the color-shape sorting task. With VF_{on}, the system will not allow child users to fail, but it will allow them to practice and get to know how sorting works. Such a system might reduce frustration in children with physical impairments, and provide more success in reaching the target containers.

For the group without disability, the VF_{off} mean values of completion times were higher than the VF_{on} mean values of completion times, overall, but only the mean values of completion times in the color-shape task were significant (Table 2). Since the complexity of the sorting task increased from one to two dimensions, the participants required more time to think about the attribute on which to sort the tokens, as well as the direction they had to take to place the tokens in the target container. This "thinking" time was reduced with VF_{on} as they could rely on the cylindrical area to guide them. Table 2 shows that the length of participants' task completion times decreased from the color task to the shape task to the color-shape task with VF_{on}. The decrease probably indicates that participants were becoming more aware of how to use the system even though the tasks were becoming more difficult. Also, some participants had memorized the movements to get to the target location in the color-shape task so they could perform the task quickly and without relying on the head-mounted display (statement e in Table 1).

The task completion times for the participant with physical impairments for the shape task and the color-shape task with VF_{off} were slightly lower than with VF_{on}. A possible reason for this was that her motion pathways during the tasks were not ideally matched with the shape of VF. As seen in Figure 5, when sorting with VF_{off}, due to her spasticity, she performed an arc-like movement which was not aligned with the straight shaped cylinder that the VFs provided to the users. Thus, the VF appears to have impeded rather than assisted the efficiency of the participant with physical impairments. Her comment in the questionnaire about fighting with the VF implies that a straight rigid shape is probably not suitable for her. One participant without disability also would have preferred an arc-shaped pathway. Overall completion times for the participant with physical impairments were much faster than for the participants without disability, which suggests some possible reasons for the completion time difference. The first reason is that the individual with physical impairments had prior experience in using haptic systems while the nondisabled participants had no prior experience. Secondly, the protocol to elicit “physical impairments” was not appropriate as far as time; visual confusion was too confusing for the participants without disability.

There was a significant difference in the area of movement in all tasks (color, shape, and color-shape) between VF_{off} and VF_{on}, with VF_{off} having a larger area of movement. Without VFs participants covered more space in the play environment when moving the token from the pick-up place to the target destination. The area of movement values of participants without disability in Table 2 were quite similar to those of the participant with physical impairments, thus, the method to elicit “physical impairments” was appropriate as far as range of movement. We may not simply conclude from our results that this system will work for children with disabilities. However, the results showed that the system could significantly restrict a users’ hand movement in the desired region, indicating that the system may be effective for our target child population. We will test the system with children with disabilities in future research.

The system had some unstable points at the edges of the cylinder where forces were applied from multiple directions, according to the cylinder formula. Participants felt a vibration that they interpreted as a nonsmooth sensation (statement c in Table 1). To reduce instability and vibrations at the edges of the VF, the shape of the forbidden region VF should have rounded edges.

Further technical improvements will include increasing the radius of the cylinder-shaped VFs and creating VFs that are more aligned with natural limb movements that will be determined for each individual. To reduce the sensation of “fighting” against the VFs during the tasks, the VF spring constant should be adjustable to make it softer or harder depending on user preference. In addition, instead of forbidden region VFs, guidance VFs could be used where the system detects the intended motion of the user and assists in attaining the intended destination, whether it is correct or incorrect. Going to the incorrect destination is desirable because children learn from their errors (25, 26).

Limitations in this study include a low participant number, a lack of washout time between task switching, and a learning carry-over effect (as seen by completion times decreasing for subsequent tasks). The area of movement was collected from only six out of ten adult participants without disabilities due to system malfunctions. Arm lengths of each participant was not considered in this study though it might have affected the task performance. Randomly selecting target locations in the color-shape task might have addressed the fact that some participants without disability were able to memorize the target locations despite visual confusion. Participants without disability replicating physical impairments is not ideal (Higginbotham, 1995), nonetheless, the study was useful to provide preliminary insight into the demands associated with haptics enabled technology for use by people who have disabilities.

4. Conclusion

The results indicate that VFs were able to restrict a user's hand movement inside a defined region and improve guidance over the movement. The success rates for both VF_{off} and VF_{on} achieved relatively high accuracy because all the participants in this study were adults. Success rates would be lower and more varied depending on the cognitive skills of child participants. VFs could be beneficial for people who have physical impairments if the rigidity of the forbidden regions and the shape of the area are determined uniquely for each individual. With further development, haptics approaches can be used to help children with physical impairments to perform playful tasks.

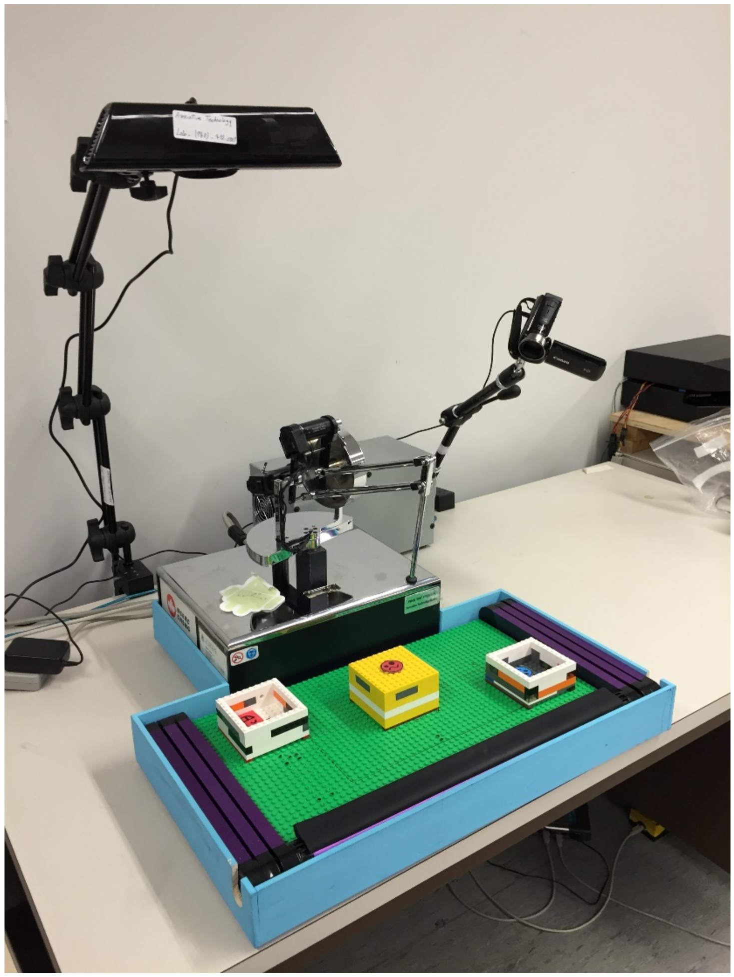

Figure 1. Robotic system and sorting activity set up. A pick-up location for tokens is located at the center of the play environment. Two destination containers are placed with one on the left side and the other on the right side of the pick-up location.

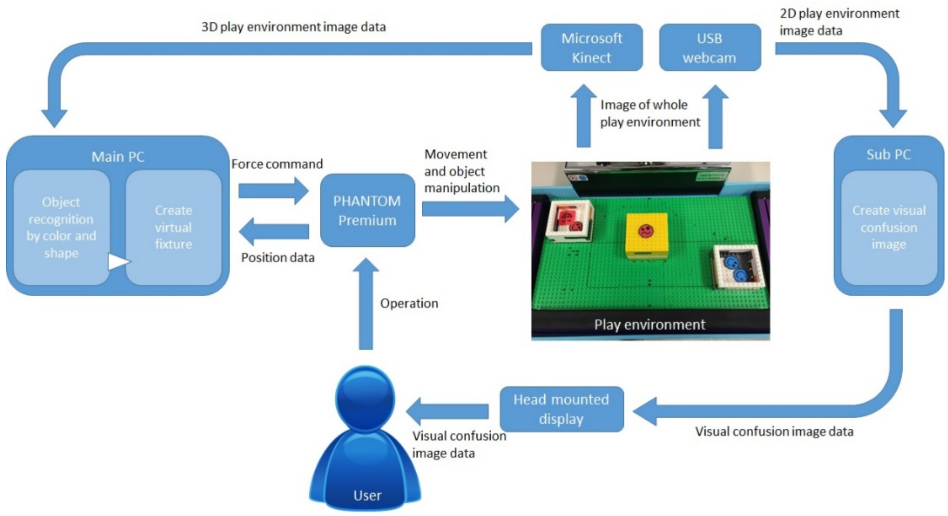

Figure 2. Schematic diagram of the system in interaction with the user and the play environment.

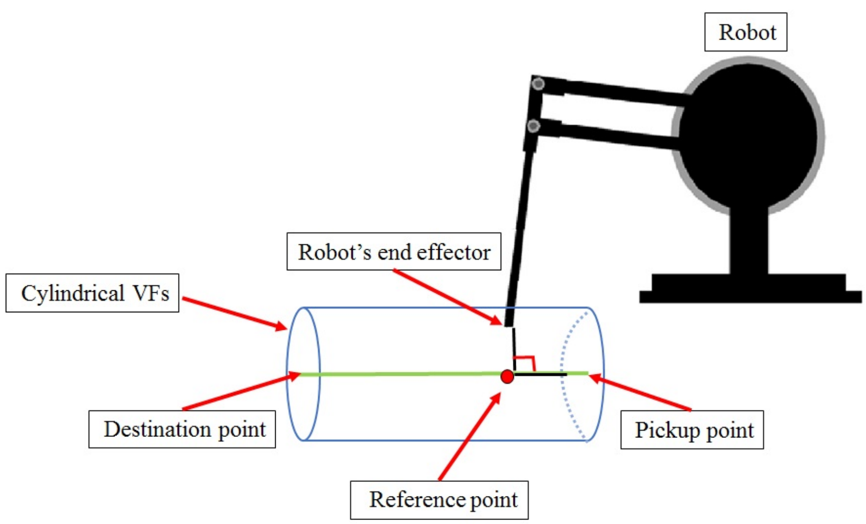

Figure 3. Illustration of the forbidden region virtual fixtures (VFs).

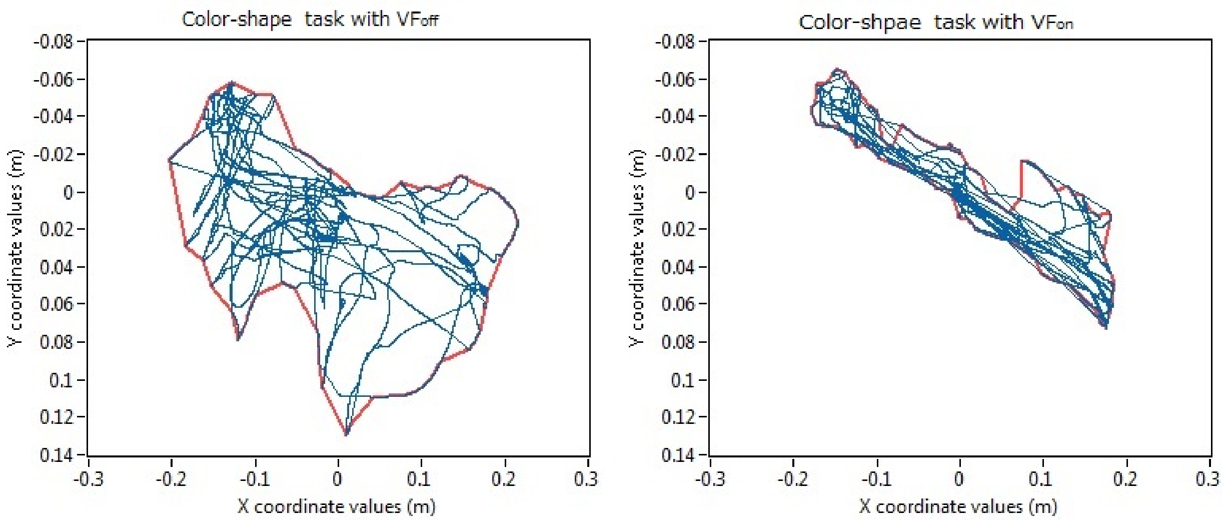

Figure 4. Trajectory and area of movement for one of the nondisabled participants.

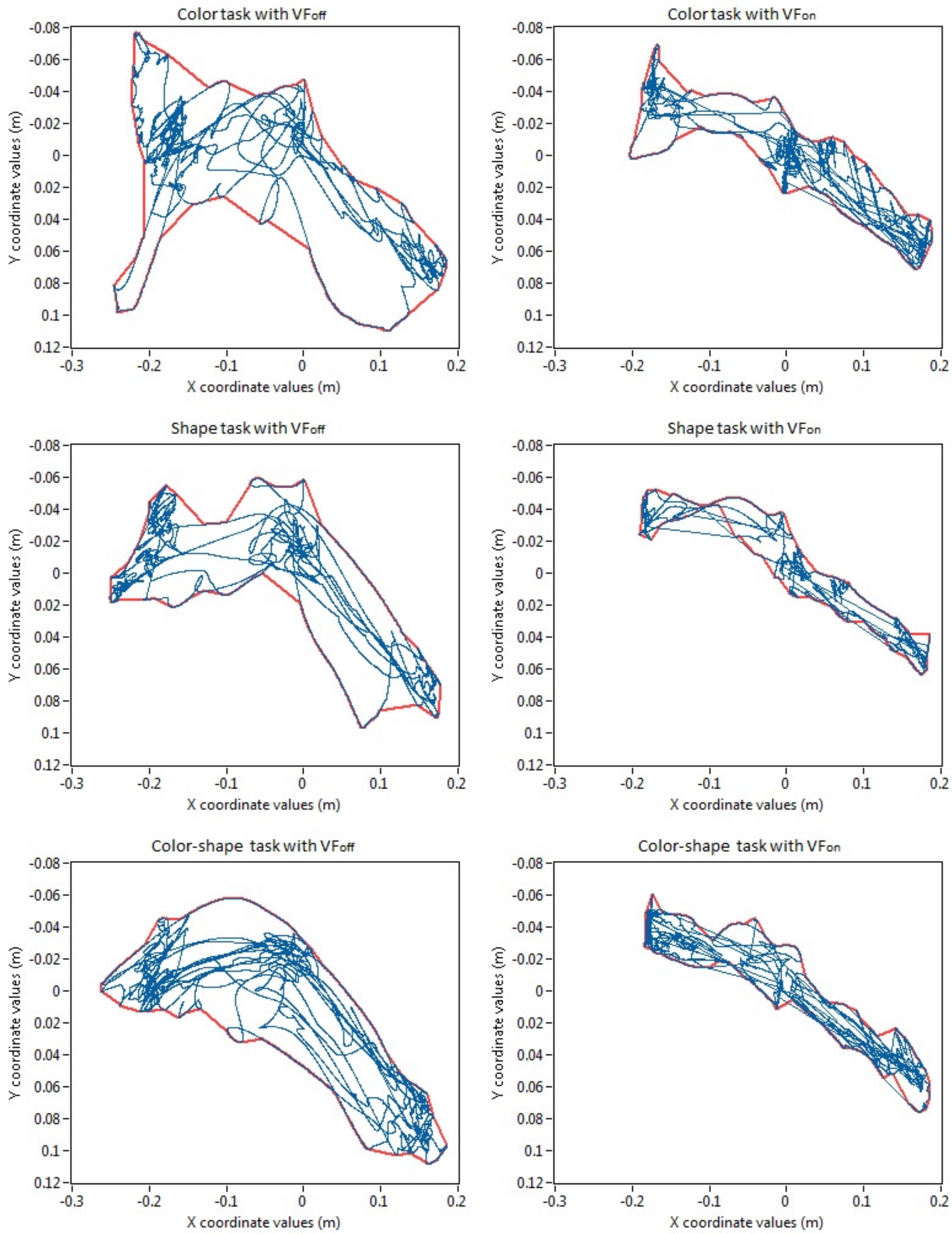

Figure 5. Trajectories and areas of movement of the participant with physical impairments.

Table 1

Participant responses to statements regarding the sorting tasks (1 = strongly disagree, 5 = strongly agree)

Question and statements regarding sorting tasks		Participant responses Nondisabled participants		Individual with physical impairments
		Range	Mode	
a) Which sorting task was easier to accomplish?	Color	NA	VF_{on}	VF_{off}
	Shape	NA	VF_{off}	VF_{off}
	Color-shape	NA	VF_{on}	VF_{off}
b) All sorting tasks were easier with VF_{on}.		1 to 5	4 and 5	1
c) When the VFs were on, the robot moved smoothly.		1 to 5	3	1
d) The video streaming of the play area was confusing.		2 to 5	2 and 5	NA
e) You relied on the video rather than memorizing the movements.		1 to 5	4	NA

NA: Not applicable.

Table 2

Mean (standard deviation) of completion time and area of movement

		Completion Time (s)				Area of Movement (m^2)			
		Nondisabled Participants		Individual with physical impairments		Nondisabled Participants		Individual with physical impairments	
Task		VF_{off}	VF_{on}	VF_{off}	VF_{on}	VF_{off}	VF_{on}	VF_{off}	VF_{on}
Color	Mean	10.12	7.57	3	1.83	0.042*	0.008*	0.034	0.014
	SD	(5.39)	(4.04)	(0.89)	(0.98)	(0.042)	(0.002)		
Shape	Mean	6.83	6.35	2.66	3	0.025*	0.009*	0.025	0.008
	SD	(1.66)	(2.31)	(1.21)	(2.28)	(0.014)	(0.003)		
Color-Shape	Mean	8.18*	4.95*	1.91	2.25	0.049*	0.011*	0.028	0.010
	SD	(5.85)	(1.46)	(0.90)	(1.05)	(0.044)	(0.003)		

*Significant difference $p < 0.05$.

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