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Development of an Assistive Robotic System with Virtual Assistance to Enhance Play for Children with Disabilities: A Preliminary Study

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Abstract

Children with disabilities typically have fewer opportunities for manipulation and play, due to their physical limitations, resulting in delayed cognitive and perceptual development. A switched-controlled device can remotely do tasks for a child or a human helper can mediate the child's interaction with the environment during play. However, these approaches disconnect children from the environment and limit their opportunities for interactive play with objects. This paper presents a novel application of a robotic system with virtual assistance, implemented by virtual fixtures, to enhance interactive object play for children in a set of coloring tasks. The assistance conditions included zero assistance (No-walls), medium level assistance (Soft-walls) and high level assistance (Rigid-walls), which corresponded to the magnitude of the virtual fixture forces.

The system was tested with fifteen able-bodied adults and results validated the effectiveness of the system in improving the user's performance. The Soft- and Rigid-walls conditions significantly outperformed the No-walls condition and led to relatively the same performance improvements in terms of: (a) a statistically significant reduction in the ratio of the colored area outside to the colored area inside the region of interest (with large effect sizes, Cohen's $d>.8$), (b) and a substantial reduction in the travelled distance outside the borders (with large effect sizes). The developed platform will next be tested with typically developing children and then children with disabilities. Future development will include adding artificial intelligence to adaptively tune the level of assistance according to the user's level of performance (i.e. providing more assistance only when the user is committing more errors).

KEYWORDS: Haptic, haptic interaction, haptic interface, virtual assistance, task performance, object manipulation, children with disabilities.

1. Introduction

Children with disabilities, whose reaching and manipulation is impaired due to their physical difficulties, may experience delayed perceptual and cognitive skills as a result of reduced opportunities for object manipulation and learned helplessness [1]. Loss of touch or haptic feedback, as one of the modes of direct manipulation, results in impaired manual exploration and object identification [2,3]. Haptics is comprised of both perception of touch (or tactile feedback) and kinesthetic (or force feedback) [4]. Haptic perception pertains to bidirectional sensory information between a human and the environment through object manipulation and environmental exploration. According to developmental theories, development of perceptual, cognitive, linguistic and social skills, particularly during infancy and throughout early childhood, rely on environmental exploration and object manipulation through different modes of exploration and manipulation including seeing, hearing and touching [5]. One can acquire unique information about surrounding environment and object properties via haptic feedback (or interaction) provided by *direct* manipulation, which cannot be perceived through other modes of exploration and manipulation [6].

Research has been carried out on *remotely* manipulating objects using switch-controlled assistive robots, controlled by head or hand switches, to facilitate task performance by individuals with disabilities, mostly in the area of play for children with disabilities [7-12]. The limitation of these assistive robots is that they do not support *direct* object manipulation, isolating children from their environment and limiting their opportunities for *interactive object play*. Here, interactive play means bi-directional child-environment interaction in which the child can directly feel and access the play environment. Furthermore, *remote* manipulation leads to the loss of haptic feedback from the object being manipulated by the assistive robot in the remote environment to the child's control interface (e.g. feeling of pushing, lifting, grasping, etc.). Thus, the child misses some environmental information.

Haptic interfaces have been used to transfer interaction forces sensed in the remote environment and to give assistance to individuals with physical limitations. A review of the applications of haptic interfaces for use by individuals with disabilities [13] revealed that the areas most frequently studied include applications for adult wheelchair users [14,15], adult computer users with physical impairments [e.g. 16] and visual impairments [17-19], and adults who had a stroke [e.g. 20]. There is very little research on the functionality of haptic technology aiming at enhancing performance in direct manipulative and exploratory tasks in people with disabilities.

Remote manipulation usually happens through a teleoperation system where the human user does not have direct contact with the environment. In one study, a teleoperation system consisting of two haptic interfaces was used to enhance the accuracy of placement of remote objects by an individual with cerebral palsy [21]. The system assisted the user by scaling her convenient range of motion up to the required dimensions of the task. Additional assistance provided by the system was (a) filtering the involuntary hand movements (or high frequency component of the motion) to enhance coordination, and (b) damping of the energy of the involuntary movements by applying 'resistive dissipative forces' at the user interface to smoothen the jerky hand movements. The system ultimately led to overall task performance improvement in a goal-oriented pick-and-place task.

Haptic-based assistance in the form of virtual fixtures (VFs) using haptic interfaces can also assist people with disabilities. VFs are defined as computer-generated assistance and are generally implemented as forbidden region VFs or guidance VFs. The forbidden region VFs helps to maintain the user's hand movements within the region of interest (ROI) by creating walls on the borders of the ROI. Guidance VFs guide the user towards a target by applying directional forces along a desired path. Previous studies have represented the mathematical modeling and design of VFs [e.g. 22]. The concept of forbidden region VFs has been mostly implemented in computer access applications, for example by creating haptic cone- or tunnel- shaped VFs around computer icons to pull the cursor towards the target [23]. Guidance VFs have typically been applied to path following and peg-in-the-hole tasks [24-27]. In a series of experimental studies, Covarrubias et al. [28-32] projected guidance VFs into a set of path following tasks, such as sketching and foam cutting, to assist adults with Downs syndrome and developmental disabilities. Implementations of VFs have demonstrated increased precision and speed performing remote tasks [26, 33, 34] and faster manipulation [27].

Virtual (or VF-based) assistance can potentially increase a child's independence during tasks by reducing the need for the physical presence of a helper. Children with disabilities often need someone such as their parents, playmates or caregivers to mediate their interaction with the environment during play. This can reduce opportunities for the bi-directional *interactive play* with the environment. In addition, the helpers oftentimes dominate children's play, which in turn reduces children's sense of independence over the play [35]. Provision of virtual assistance could give children a sense of independence over task execution and provide the assistance needed to be more successful in the task execution.

Coloring is a playful way to facilitate a child's fine motor skills, artistic thoughts, focused attention and imagination [36,37]. It starts with initial scribbling in toddler years and later, the obtained skills evolve into the meaningful symbols and drawing [36] and use of writing tools [38]. Children may first press very hard on the coloring surface, and color the whole page but they gain physical skill and fine motor control through repetition over time and learn to use appropriate force and stay within the lines. However, children with disabilities who have fine motor deficits, such as hand tremor or spasm, often lack the required skills for coloring that involves coordination and fine motor movements. They may cross the borders, color a large area outside the ROI, and scribble all over the sheet instead of coloring inside the intended ROI. As a result, the child may require help or experience frustration or disappointment. A child's self-efficacy may also be affected. Self-efficacy contributes to one's belief in his/her personal capabilities to succeed in a specific task, which highly relies on the past performance and experiences [39]. In the event of failure or poor performance, children may become more vulnerable to fail, less optimistic about their abilities and show loss of motivation and self-efficacy [40].

The use of haptic-based assistance may enable some children with disabilities to be successful in the physical task of coloring. A haptic interface could be adapted to accommodate a child's abilities such as range of motion, and various grips could be attached to the interface to match the grasp ability of the child. Provision of forbidden region VFs, as needed, can potentially improve the overall accuracy. Additional assistive features such as dampening, the approach taken by Atashzar et al. [21], could facilitate movement difficulties such as hand tremor, or coordination deficits. However, before using haptic-based interfaces with children with disabilities, testing the system with adults without disabilities can inform system performance and design, since adults are able to articulate opinions. Later, testing with children without disabilities, can inform possible implications for use by children with disabilities such as cognitive and perceptual demands.

1.1 Purpose

The purpose of this study was to validate the effectiveness of a forbidden region VF system for coloring with adult users who had never used a robotics system before. This paper specifically examines a new application of virtual (or VF-based) haptic assistance to enable robotic-assisted access to manipulation of a play environment for coloring, which could ultimately lead to overall task performance improvement. Two types of tasks were performed, exploring forbidden region VFs and coloring. For exploring, a novel and systematic procedure called "System Validation by Virtual Object Exploration" was performed to test and validate the robotic system in terms of its stability, safety and perceptibility of the implemented forbidden region VFs. The exploration task was evaluated based on the user's opinions upon completion of the task. The coloring task tested the effectiveness of the VF-based assistance on user's performance and involved coloring some template ROIs images on a tablet computer. Forbidden region VFs were imposed on the borders of the ROI in order to assist the user's movements to stay inside the ROI while coloring. Each coloring operation was carried out under three assistance conditions corresponding to the rigidity of the forbidden region VF walls including no assistance, a medium level and a high level of assistance. The goal was to compare different conditions of assistance and determine their effect on coloring performance. The research objectives were:

1. To validate the system, with able-bodied adults, in terms of stability and safety, and perceptibility of the implemented forbidden region VFs through virtual object exploration tasks.
2. Compare the user's performance in the coloring tasks between no assistance, and medium and high level of assistance in terms of ratio of the colored area outside to the colored area inside the ROI, travelled distance outside the ROI (displacement) and number of collisions with the borders of the ROI.

2. Method

A preliminary evaluation of the system with abled-bodied participants was used to reveal the possible technical demands or required modifications in the system or the tasks. A repeated measures design across all subjects was applied to test the effectiveness of each assistance condition on performance. Fifteen able-bodied adult participants were recruited among <blinded for review> grad students. The inclusion criteria were able-bodied adults 18 to 65 years old with no motor difficulties in arms and hands. Attention, cognitive and hearing impairments were the exclusion criteria.

2.1. System Description

As shown in Fig.1, the experimental setup consists of a desktop haptic interface PHANToM Premium 1.5A (Geomagic, Cary, NC) as the user interface, a tablet computer which plays the role of the coloring surface, and a wooden box to hold the robot and tablet steady. As outlined by Jafari et al.[13], the Premium has a serial kinematic design, despite its parallel linkages, providing a flexible workspace in terms of the robot range of motion, 381 W x 267 H x 191 D mm. In addition, the Premium has a pen-shaped stylus that makes it appropriate for the coloring operation by acting as a coloring pen. The Premium is interfaced to a PC via a parallel port using a Phantom Communication Converter and FireWire Card (requires IEEE-1394a-2000 compliant FireWire Port).[1] Quark software (Quanser Inc., ON, Canada) was used for interfacing the robot with the computer. Quark is a real-time control software toolbox developed and integrated into Simulink toolboxes in MATLAB to support some haptic devices including the Premium. The tablet was placed within the reachable workspace of the Premium.

[1] http://dl.geomagic.com/binaries/support/downloads/Sensable/3DS/Premium1.0_1.5_HF_Device_guide.pdf

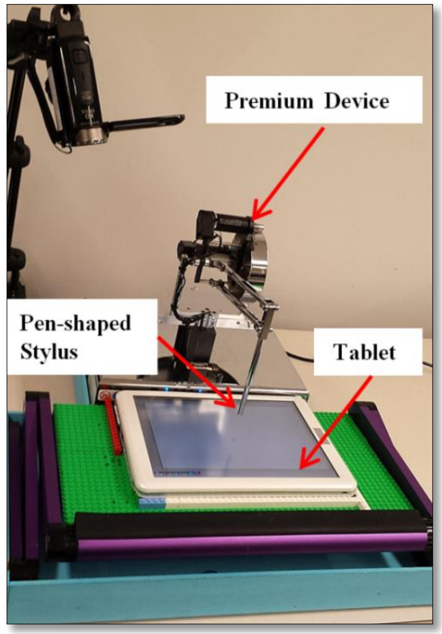

Fig. 1 The experimental setup consisting of a 3-DOF PHANToM Premium device with a pen-shaped stylus, and a tablet computer

2.2. Virtual Assistance

Note that VFs in the remainder of this paper refers to the forbidden region VFs that were implemented for this system. The VFs used prior knowledge about the shapes of the desired ROIs to be colored and imposed virtual walls on the borders of the ROIs. VFs were developed and implemented as spatial open-ended cylindrical and cubical objects. Thus, a user would feel a cube or a cylinder surrounding the robot's arm end-effector when moving it around in 3D space. Side views of the 3D VF-shaped cylinder and cube are shown in Fig. 2, as obtained by continuously moving the robotic arm on the inner surface of the VFs. The projection of the cylindrical and cubical VFs on an *xy* plane (e.g. the tablet) generates 2D ROIs roughly resembling a circle (radius=2.25cm), and square (side length=5.5cm), respectively. Due to a discrepancy in the robot's encoders, the *y* values changed when moving the robot's end-effector along an arbitrary $y=a$ line (a = constant). This resulted in having an ellipse (minor axis=6.2cm, Major axis=6.5cm) and a rectangle (width side=7cm, length side=7.5cm) when enlarging the shapes. The large ROIs were generated to test possible performance differences with different sized shapes. Four corresponding template 2D ROIs (e.g. resembling a circle, a square, an ellipse, and a rectangle) were saved as images on the MS Paint program on the tablet as template ROIs for the coloring tasks.

In the case of the cubical-shaped VFs, VF_{cube}, four points were determined as the vertices to create the corresponding faces of the cube. Two more points, P_{s1} and P_{s2}, were assigned, which generated the centerline of the cube.

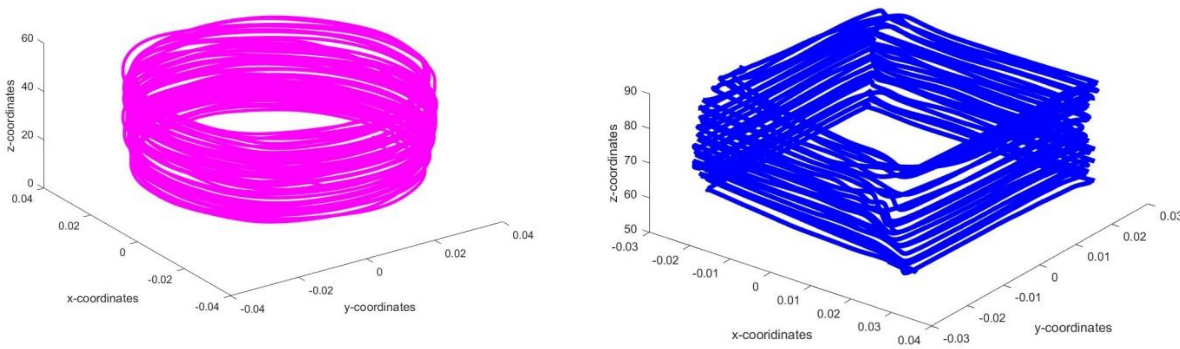

Fig. 2 Visual illustration of the cylindrical- and cubical -shaped VFs

The VF_{cube} was implemented as a spring model system connecting the current position of the robot's end-effector, P_{e-e}, with an Euclidean point, $P_{Euclidean}$ (as shown in Fig. 3). The $P_{Euclidean}$ was calculated in real time (with a sample rate of 10kHz) by the inner product of the P_{e-e} and the cube centerline that generated the Euclidian distance, $distance_{Euclidean}$. The P_{e-e} being outside the walls implied that a collision incident had happened (defined as P_{e-e} being on the border of the ROI) and that the distance from the P_{e-e} to the $P_{Euclidean}$ ($distance_{current}$) was greater than the $distance_{Euclidean}$. If this condition held true, the VF_{Cube} forces were generated as follows:

$$VF_{cube} = \begin{cases} k * displacement, \ if \ distance_{Euclidean} < distance_{current} \\ 0 \qquad , \qquad Otherwise \end{cases} \tag{1}$$

$$displacement = distance_{Euclidian} - distance_{current} \tag{2}$$

where k, the gain ratio of spring, determines the magnitude of the force. The larger the k value, the greater the VF_{cube} forces and therefore, the more rigid the walls of the cube. The linear relationship of the force and displacement implied feeling a small force when just coming into contact with the walls and a gradual increase of the force when pushing further against the walls. This was to prevent the exertion of a sudden force to the robot, which could lead to instability issues. The VF_{cube} forces in the *z*-direction (the top and bottom faces of the cube) were set to zero for the purpose of letting users freely move the robotic arm along the height of the cube. There was zero force when navigating inside the cube, while directional forces were generated when hitting the walls. The direction of the force was determined by the vector connecting $P_{Collisions}$ and P_{e-e} which was applied so as to push the user away from the walls and towards the $P_{Euclidian}$:

$$direction = \frac{P_{collision} - P_{e-e}}{norm(P_{collision} - P_{e-e})} \tag{3}$$

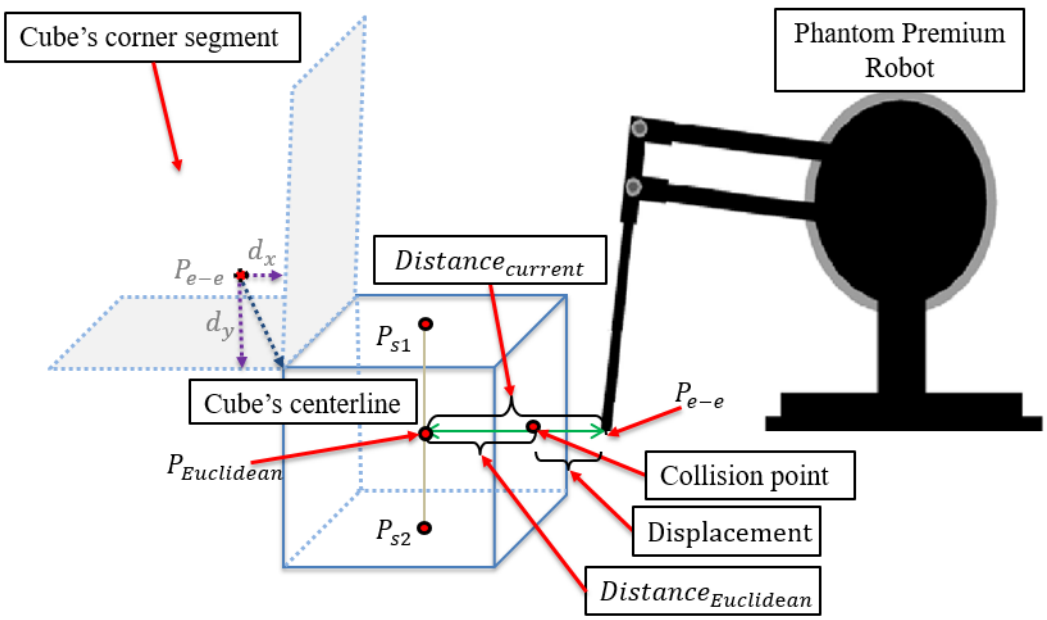

Fig. 3 Illustration of the implementation of the cubical-shaped VF forces when the robot crosses over the ROIs. Two samples points, P_{s1} and P_{s2}, and a sample $P_{Euclidean}$ are shown

It should be noted when P_{e-e} was located at any of the cube's corner segments (as depicted in Fig. 3), displacement was calculated based on the Pythagorean Theorem of the *x* and *y* projections of the P_{e-e}, d_x and d_y, on the closest face of the cube:

$$displacement_{corner} = \sqrt{d_x^2 + d_y^2} \tag{4}$$

This was to direct the robot's stylus towards the nearest vertex and to take the shortest distance to return to the cube.

The same logic was applied to implement the cylindrical-shaped VFs, $VF_{cylinder}$ except that implementation of the cylinder required less computation. By knowing the cylinder's CenterPoint and radius, the P_{e-e} was tracked until a collision happened. This implied that the $distance_{current}$ was greater than the cylinder radius and thus, $VF_{cylinder}$ were generated.

2.3. Virtual Assistance Conditions

By setting the gain ration, *k*, three different levels of assistance were generated, each associated with a specific level of virtual wall rigidity, namely No-walls, Soft-walls, and Rigid-walls. Assistance approaches were as follows:

No-walls: This approach was to obtain a baseline condition where no assistance was provided. Accordingly, a user accomplishes the tasks without VF assistance, which provides an indication of an individual's typical performance.

Soft-walls: In this approach, the rigidity of the implemented VFs were set to a medium level to not entirely constrain the movements, but still allowing a user to feel the VF forces on the ROI's borders. This resembles a sensation of moving through gel when pushing against the VF walls. This way, a user maintains some control over the movements when coming into contact with the walls while it is still possible to cross over the borders (thus, coloring outside of the lines).

Rigid-walls: In this case, the movements of the stylus were rigidly constrained to the specified ROI providing maximum control for staying inside the ROI. This setting results in fewer chances of crossing over the borders, which in turn reveals the maximum performance available from the system. A user can still move the stylus freely inside the ROI in any direction.

3. Procedure

The following describes the protocol that was developed to systematically test and validate various features of the system.

3.1. Experimental Task 1 - System Validation by Virtual Object Exploration

A procedure, virtual object exploration, was established to test the validity of the system in terms of its *stability* (i.e. no vibration of the robot was sensed by the user) and *safety* (i.e. the robot did not go out of control) as well as the *perceptibility* of the implemented VF_{cube} and $VF_{cylinder}$. Exploration was carried out only with the Rigid-walls condition. This was to ensure that the objects were clearly tangible. The participants were expected to *explore the contour* (or the inner surface) of the virtual spatial objects by holding the robot stylus with their dominant hand. Prior to starting, the participants were given a brief description of the required hand movements to continuously maintain the tip of the robot's stylus on the inner surface of the virtual objects. This procedure was in accordance with the '*contour exploration*' procedure outlined by Lederman and Klatzky (1987): "dynamic exploratory procedure in which the hand maintains contact with a contour of the object" (p. 347). Participants' speed and interaction forces with the virtual objects could contribute to the overall perception. Therefore, the participants were also instructed to maintain a medium (not too large, not too small) amount of speed and force throughout the exploration. This procedure was aligned with the Occupational Therapy definition of *calibration skill* as "using movements of appropriate force, speed, or extent when interacting with task objects (e.g., not crushing objects, pushing a door with enough force that it closes)" [41, page 1237]. Eventually, the participants were asked to identify the shape of the explored objects taking as much time as needed until they could identify the shape.

3.2. Experimental task 2: Validation of Virtual assistance in Coloring

In order to systematically assess the contribution of VF assistance, coloring tasks were carried out for the four ROIs (circle, square, ellipse and rectangle) and the three different levels of assistance (No-walls, Soft-walls, and Rigid-walls). Both Soft- and Rigid-walls were tested to examine participant preference as well as best performance. The intention was to determine the appropriate amount of assistance that made the user feel being assisted but not resisted.

The order of coloring tasks was kept the same to facilitate technical implementation of the protocol. The assistance levels were counterbalanced before the session to control for order effects [42]. The assistance level was blinded to the participants. Participants were asked to use their non-dominant hand to color inside the ROI templates. The use of non-dominant hand was intended to increase the challenge and sensitivity to detect benefits from virtual assistance. Participants were given a limited amount of time (11sec for smaller and 12sec for bigger ROIs). Reasonable amounts of time for each task were determined from pilot tests. The participants were aware there was a time limit but were not told how much time they had. The participants were prompted to color as fast as possible and cover as much area as possible within the given time and to firstly aim for the areas close to the borders; this was to ensure the VF-walls were engaged during the performance. Observation notes were taken by author 1 during the sessions to document the interaction of the participants with the VF-walls.

4. Data Collection and Analysis

The participant's report of shape of the explored object, and the time to make the identification were recorded. The level of system stability and safety and the VFs' perceptibility in the exploration task were assessed on the basis of a Likert 5 point scale [43], where 1 = *strongly disagree* and 5 = *strongly agree*) in response to the statements displayed in Table 1. The position data was collected to plot the user's data in the coloring tasks. The performance was measured on the basis of the following *Quantitative robot measures* (dependent variables, DV) including:

1. *Ratio of Colored area outside to the colored area inside* the ROI ($\text{Ratio}_{\text{out-in}}$) that described the proportion of the amount of the colored area outside the template ROI to that of inside. It should be noted that the points on the border were considered as inside area since the

positional displacement is zero on the borders and therefore, $VF = k * displacement$=0.

2. *Positional displacement* of the robot stylus from the borders of the ROI (Displacement) that described error at each sample time (as shown in Fig. 3)
3. *Number of collisions* with the borders of the ROI (#OfCollisions). It was considered a collision when the robot stylus went outside of the ROI. The return to enter inside the ROI was not considered as a collision.

Qualitative measures including a *Robot usability questionnaire* (Table 2) was administered at the end of the session to assess the participants' overall insight into the system. The questionnaire statements were based on the System Usability Scale (SUS) [44] and were modified to fit the current system and tasks. The goal was to provide insight into the features of the system including: ease of use, effectiveness of the system and the actions taken by the system (e.g. the implemented VFs), reliability and safety, and usefulness. Statements on stability, safety and perceptibility (as indicated in Table 2) were conceptually similar to the survey questions used in the exploration task, but in this case assessed the participant's overall perception of the system.

Table 1 Survey questions administered after completion of the explorational task

Feature of the system & VFs	Survey questions	Additional clarification, if needed
Stability	The system was stable.	No vibrations were sensed on the robot.
Safety	The system was safe to work with.	The robot didn't go out of control.
Perceptibility	The contours and edges of the virtual objects were clearly tangible on the robot.	The VFs were properly implemented and the virtual objects (cylinder and cube) were perceivable.

Table 2 Usability robot questionnaire administered at the end of the session. The numbers indicate the order in which the questions were asked

SUS Category: Feature of the system & virtual assistance	Associated robot feature	Usability robot questionnaire
Ease of use	-	1. The system can be used without much training.
Reliability of the system	Safety	3. I felt confident using the system.
Reliability of the system	Stability	6. The system was stable (there was no vibration).

Effectiveness of the system	-	4. I think the system helped me to do the coloring task more easily and quickly.
Effectiveness of actions taken by the system	-	2. The virtual forces were effectively applied into the coloring tasks.
Effectiveness of actions taken by the system	Perceptibility	5. The contours and edges of virtual objects were clearly tangible on the robot.
Usefulness (or effectiveness) of actions taken by the system	-	7. I didn't feel any forces when I was moving the robot inside the virtual objects.

Algorithms were developed in Matlab to analyse the amount of colored area inside and outside the ROIs, displacement, and the number of collisions. One-way ANOVA measures (within-subjects factors) with Bonferroni correction were performed to determine whether there was a significance ($p<.05$) between the three VF assistance conditions (No-walls, Soft-walls and Rigid-walls) on the user's performance. The Mauchly's Test of Sphericity was conducted to examine the homogeneity of variances. Effect sizes were reported as Cohen's d statistics (*d*) [45]. The questionnaire responses from participants were described by the parametric statistics of median, mode and range.

5. Results

This section presents the results of the two experimental tasks: 1) virtual objects exploration as assessed by the survey questions, participant's responses to object identification and elapsed time, and 2) coloring as assessed by the quantitative robotic measures including the $Ratio_{out-in}$, Displacement, and #ofCollisions. Finally, the results of the overall insight into the system and its features as assessed by the robot usability questionnaire are presented.

5.1. System Validation by Virtual Object Exploration

Almost all participants endorsed "strongly agree" for all three survey questions (Mdn = 5, Mode = 5, Range from 4 to 5).

The average time to identify the shape of the virtual objects was 20:05 seconds for the circle and 10:53 seconds for the square. Eleven out of fifteen participants correctly perceived the shape of cylinder (or circle on the surface); two subjects had similar guesses (e.g. mentioned egg-shape and oval) and two failed to perceive the shape (e.g. mentioned triangle and diamond). All participants perceived the shape of the cube (or square on the surface); three of them perceived a rectangle, which was considered a correct answer since the user only relied on spatial inspection and could not visually discriminate the side lengths.

5.2. Validation of Virtual Assistance by Coloring

5.2.1. Quantitative Robot Measures

In the following, the results of the ANOVA Bonferroni correction test are presented (Table 3). The underlying test of Sphericity and Normality were met ($p < .05$) for the dataset. Although the measure of #ofCollisions was decreased in most cases in the presence of either Soft- and Rigid-walls, the overall differences were not large. This can be explained by the VF equation generating zero force on the borders as a result of zero displacement. This implies the software counting any cross over as a collision incident even if the user had only a slight touch with the borders. Therefore, the corresponding results were excluded from further analysis.

Table 3 ANOVA test results for different assistance conditions within the four tasks using Bonferroni correction

Task	VF assistance condition		Measures	Dependent variables	
				$Ratio_{out\text{-}in}$	Displacement(mm)
Circle	**No-walls**	**Soft-walls**	*p*	<.001*	<.001*
			Effect	2.88	2.80
			MeanDiff	0.24	2.87
		Rigid-walls	*p*	<.001*	.001*
			Effect	2.45	2.55
			MeanDiff	0.22	2.75
	Soft-walls	**Rigid-walls**	*p*	1.0	1.0
			Effect	.21	-.14
			MeanDiff	-0.02	.11
Square	**No-walls**	**Soft-walls**	*P*	<.001*	.1
			Effect	1.60	.85
			MeanDiff	0.11	2.49
		Rigid-walls	*p*	<.001*	.1
			Effect	2.23	.74
			MeanDiff	0.14	2.36
	Soft-walls	**Rigid-walls**	*p*	.5	1.0
			Effect	.48	-.1
			MeanDiff	0.02	-.13
Ellipse	**No-walls**	**Soft-walls**	*p*	.003*	.05*
			Effect	1.14	1
			MeanDiff	0.06	1.91
		Rigid-walls	*p*	.003*	.005*
			Effect	2.29	1.5
			MeanDiff	0.11	3.05
	Soft-walls	**Rigid-walls**	*p*	.003*	.006*
			Effect	1.23	1.33
			MeanDiff	0.05	1.138
Rectangle	**No-walls**	**Soft-walls**	*p*	<.001*	<.001*
			Effect	1.83	1.91
			MeanDiff	0.15	2.93
		Rigid-walls	*p*	<.001*	<.001*
			Effect	1.93	1.89
			MeanDiff	0.16	3.08
	Soft-walls	**Rigid-walls**	*p*	.6	1.0
			Effect	.22	.21
			MeanDiff	0.01	.15

*Statistically significant difference $p < .05$.

In Table 3, the effect of altering assistance conditions on performance are presented in terms of the level of significance (*p*), Cohen's *d* effect size (*d*) and mean difference between the conditions (*MeanDiff*). Note that a negative *MeanDiff* indicates that the corresponding dependent variable value decreased from the first condition to the second. In the following, the effect of each assistance condition on users' performance in terms of the two dependent variables ($\mathbf{Ratio_{out\text{-}in}}$ and **Displacement**) are summarized. The mean differences and standard deviation errors are represented in Figs. 4 and 5. Also, scatter plots of the performance of participant #1 under all conditions in terms of the colored area inside and outside of the template drawings are illustrated in Appendix A (Figs. 6 to 9).

Soft-walls condition**:** As shown in Table 3, the user's performance improved significantly, compared to typical performance (No-walls), when Soft-walls assistance condition was provided. Large effect sizes with statistically significant differences between the No-walls and Soft-walls conditions occurred in terms of the $\mathbf{Ratio_{out\text{-}in}}$, meaning that the users colored less area outside the template shapes and therefore, more of their time was devoted in coloring the inside area (Circle: d=2.88, p<.0001; Square: d=1.6, p<.0001; Ellipse: d=1.14, p<.003; Rectangle: d=1.83, p<.0001). Also, a significant reduction in the travelled distance outside the lines (**Displacement**) was obtained, as indicated by the large effect sizes between the No-walls and Soft-walls conditions (Circle: d=2.80, p<.0001; Square: d=.85, p=.1; Ellipse: d=1, p=.05; Rectangle: d=1.91, p<.0001).

Rigid-walls condition: In the presence of Rigid-walls assistance, the same trend as for the Soft-walls condition emerged. The user's performance improved as seen by the large effect sizes with statistically significant differences between the No-walls and Rigid-walls conditions, as assessed by the $\mathbf{Ratio_{out\text{-}in}}$ (Circle: d=2.45, p<.0001; Square: d=2.23, p<.0001; Ellipse: d=1.14, p<.003; Rectangle: d=1.83, p<.0001). In addition, the travelled distance outside the lines, **Displacement**, was significantly reduced as indicated by the large effect sizes for Circle (d=2.55, p=001), Ellipse (d=1.5, p=.005) and Rectangle (d=1.89, p<.0001), and medium effect size for Square (d=.74, p=.1).

Soft-walls compared to **Rigid-walls** condition**:** The Soft-walls and Rigid-walls conditions overall did not show significant differences from each other. There were small effect sizes between the two conditions for all tasks. Only for Ellipse, large effect sizes were obtained (**Ratio$_{out-in}$**: d=1.23, p=.003; **Displacement**: d=1.33, p=.006).

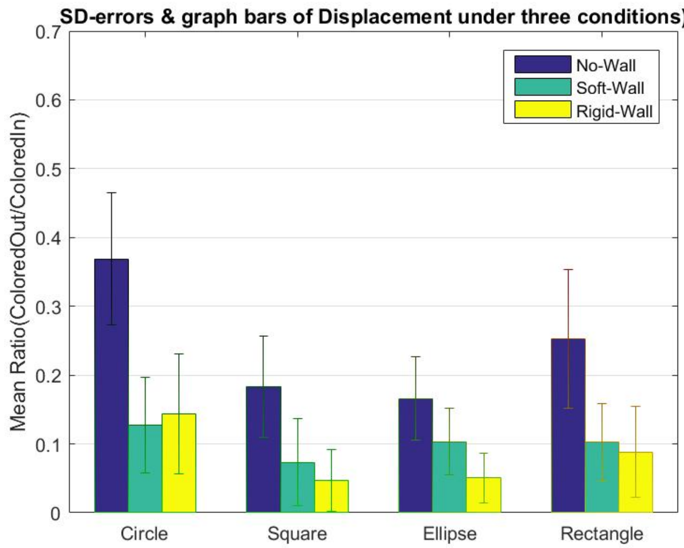

Fig. 4 Illustration of mean variances of the Ratio of the ColoredAreOut to the ColoredAreaIn under different assistance conditions. The Ratio has significantly decreased by altering from No-walls to either Soft- or Rigid-walls conditions

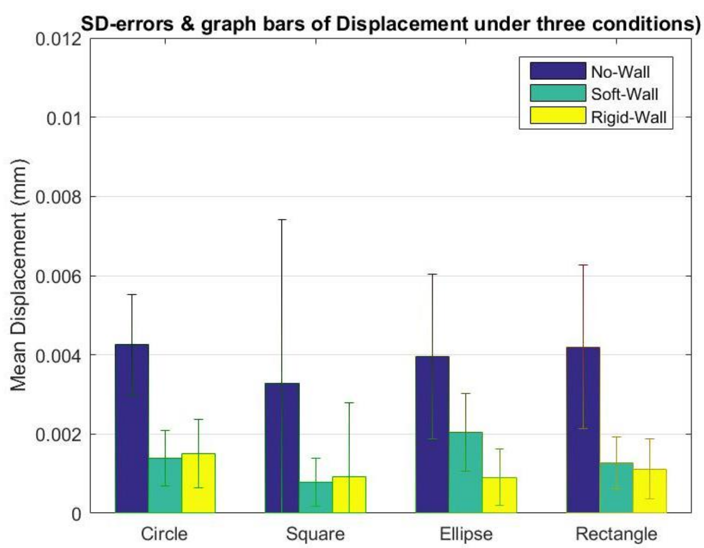

Fig. 5 Illustration of mean variances of Displacement under different assistance conditions. The Displacement has significantly decreased by altering from No-walls to either Soft- or Rigid-walls conditions

5.2.2. Qualitative Measures

The responses and comments of the participants are presented in Table 4.

Table 4 Results of the participants' responses to the robot usability questionnaire administered to assess the overall features of the system and the implemented VF-based assistance

Questions (evaluated feature)	Mdn	Mode	Range	Summary of comments
The system can be used without much training (ease of use).	4	5	2 to 5	Several participants referred to the system as easy and fun to work with.
The virtual forces were effectively applied into the coloring tasks (effectiveness of actions taken by the system)	5	5	1 to 4	There were comments saying that the participants liked how the virtual forces helped to stay inside, felt more controlling with forces than without, and found coloring a lot easier when borders were on.
I felt confident using the system (reliability (or safety) of the system).	5	5	2 to 5	No comments.
I think the system helped me to do the coloring task more easily and quickly (effectiveness of the system).	5	5	3 to 5	Some of the participants found the "handle" (the robot's metallic stylus) slippery and suggested to add some texture into it, although it was comfortable. One participant stated that she had to modify her grip to hold the grip straight up and down and may need some time getting used to.
The contours and edges of virtual objects were clearly tangible on the robot (effectiveness of actions taken by the system).	5	5	3 to 5	One participant commented that the virtual shapes were "amazingly" tangible.
The system was stable and there was no vibration (reliability (or stability) of the system).	5	5	3 to 5	One participant misperceived the concept of VF walls and thought of them as vibration.
I didn't feel any forces when I was moving the robot <u>inside</u> the virtual objects (usefulness).	5	5	1 to 5	No comments.

5.3. Observations and General Comments

A few of the participants gave additional comments regarding the shape and size of the VF-shapes. They thought that the square (or rectangle) was more difficult than the circle (or ellipse) as they needed to deal with the corners while the circle required more natural hand movements and they did not need to modify or over compensate movements. Also, one participant noticed that she was making a certain pattern of movements when the VFs were on while making more random movements when it was off.

It was observed that instead of continuously moving the tip of the robotic arm on the surface of the objects, a few of the participants randomly moved the arm from one spot to another. This resulted in mistakenly feeling several angles on the virtual object. Also, it was observed that for a few of the participants the VF-walls were initially not intuitive to interact with and they seemed very conservative when coming into contact with the walls. But after some practice, they seemed confident to hit or push against the walls.

6. Discussion

In this preliminary study, the validity of the developed system was initially confirmed based on its stability and safety. There was no incident of the robot going out of control and all participants felt the system was safe, as assessed by the survey questions and participants' comments. In addition, none of the participants experienced any source of vibration or noise; moving the stylus in the sharp corners of the square VF had the potential to cause the system to become unstable due to the sudden change of the force magnitude and direction but it stayed stable. The validity of the generated VFs was also confirmed by correct perception of the shape of the virtual objects. Only two participants mistakenly perceived a diamond and a triangle instead of the circle. Additionally, the participants' overall ratings and comments about the system confirmed the system's ease of use, reliability, safety and stability, as well as the effectiveness of virtual assistance in performing coloring faster and easier. None of the participants exhibited difficulty operating the system. As for the question on usefulness, responses showed that the participants did not feel any forces inside the virtual objects. Thus, the software did not apply unnecessary force when navigating inside the ROIs.

Soft-walls and **Rigid-walls** conditions led to the best performance improvements with large effect sizes in terms of a substantial reduction in $Ratio_{out-in}$ error, and a great reduction in Displacement. Therefore, we can conclude that, regardless of shape and size of virtual objects, the virtual assistance (either Soft or Rigid) did successfully decrease the total error and elicited a significant increase in coloring performance in maintaining the movements inside the ROI borders. In terms of the #OfCollisions, it decreased in most cases in presence of the VF assistance (either Soft or Rigid); however, it was overall not a strong indicator of the user performance to track. The Soft- and Rigid-walls led to relatively the same performance improvements over No-walls. A possible reason is that our participants were abled-bodied adults who were able to maintain their control when touching the forces (either small or large) at the borders, despite being challenged by the time constraint and use of non-dominant hand. We might expect higher performance improvements with the Rigid-walls condition in future studies with children who have disabilities due to their less controlled fine motor movements.

The Rigid-walls approach enabled participants to better stay within the ROI borders, however, a few of the participants commented that they preferred the Soft-walls because they found the Rigid-walls somewhat restricting. This is a valid point to consider when user's satisfaction is a priority.

The fact that a few of the participants made different movements when VFs were on (either hard or soft) can be a valid point for applications in which the human user needs to learn a certain pattern of movement to accomplish a specific task.

When children with and without disabilities use the system, we would expect similar results as the adults in terms of $Ratio_{out-in}$ and Displacement, i.e., the forbidden region VFs (both Soft- and Rigid-walls) will maintain the movements inside the ROI compared to No-walls. There may be differences in how adults and children perceive the forces, however, execution of the task does not rely on how well the user perceives the rigidity of the implemented haptic-based virtual assistance. The virtual assistance is imposed regardless of how well the virtual walls .can be perceived The differences in how adults and children perceive forces may result in different results from the adults for Soft- and Rigid-walls. For the adults they maintained control regardless of the wall, Soft- or Rigid, but that may not be the case for children. Future studies with children at various ages are needed to evaluate how they perceive VFs, and with what resolution.

It may be appropriate for children with disabilities to select their preferred assistance condition (either Soft or Rigid) for higher satisfaction. Or, the system could adapt automatically as children improve in the task over time. If the child begins to color within the defined borders, less assistance (less stiff walls) might suffice. This may give children a feeling of control over the task, letting them do the task as independently as possible. It is preferable to only provide assistance as needed, without imposing unnecessary force or restriction on the operator.

In long term studies with children with disabilities, enhanced play performance in children may contribute to increased satisfaction, sense of independence, self-efficacy and motivation in the coloring activity. However, studies with typically developing children are needed first to understand if the system presents cognitive and sensory demands that may affect performance, satisfaction, and independence.

This study had some limitations yet to be mentioned. There was a high variability in data, likely occurring as a result of performance differences in abled-bodied participants using their non-dominant hand. There would also likely be high variability in group studies with children, due to their unique impairments. Thus, study designs where participants are their own controls will be needed. Also, the participants were asked to firstly color the area close to the borders to ensure the engagement of the VF walls in performance. This may have changed the naturalness of the coloring action. In future studies, participants will not be given any prompts in this regard. The issue with the robot encoders' discrepancy when creating symmetrical shapes will also be addressed in future development. A texture will be added to the robot's metallic stylus to prevent it from sliding out of the operator's hand.

Further development of the system will include integration of intelligence into the system to adaptively tune the level of assistance (i.e., rigidity of the virtual walls) according to the user's performance. In future studies with children, the measures of Min and Max of Displacement will also be reported for additional assessment of child's performance. Integration of guidance virtual fixtures can assist the children's hand movements to initially create a drawing and then color inside it.

7. Conclusion

This study presented the preliminary evaluation of the developed system with able-bodied adults. The system's safety and stability as well as the perceptibility of the implemented virtual objects were clearly validated. The user's typical performance (No-walls condition) was compared against the Soft-walls and Rigid-walls assistance conditions. The results validated the effectiveness of both assistance conditions in improving the performance of the user as confirmed by the 1) significant decrease in the ratio of the colored area outside to the colored area inside the ROI, and 2) a great reduction in total displacement from the borders of the desired region. Soft and Rigid walls did not lead to big performance differences, however the Soft-walls were more preferred by some of the participants. Future experiments will address the effectiveness of the proposed system in assisting children without and with disabilities.

Acknowledgments

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Appendix A

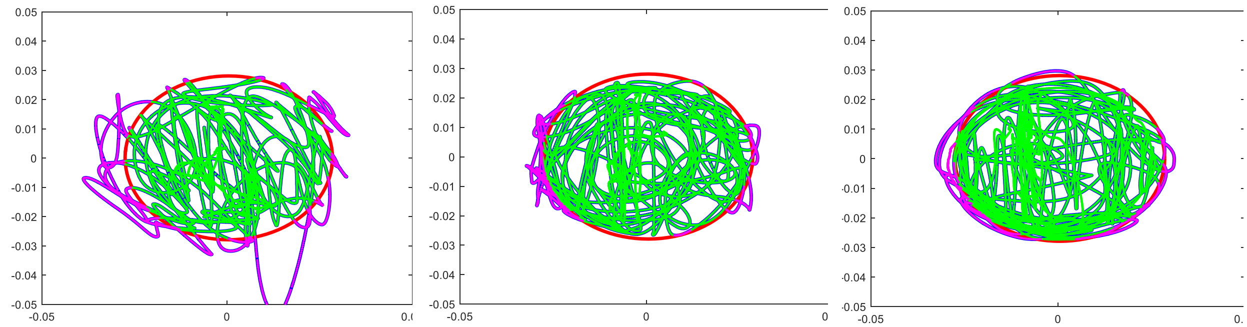

Fig. 6 Illustration of the color-coded movement trajectories of participant #1 inside and outside the ROI under No-walls (left plot), Soft-walls (middle plot) and Rigid-walls (right plot) assistance conditions

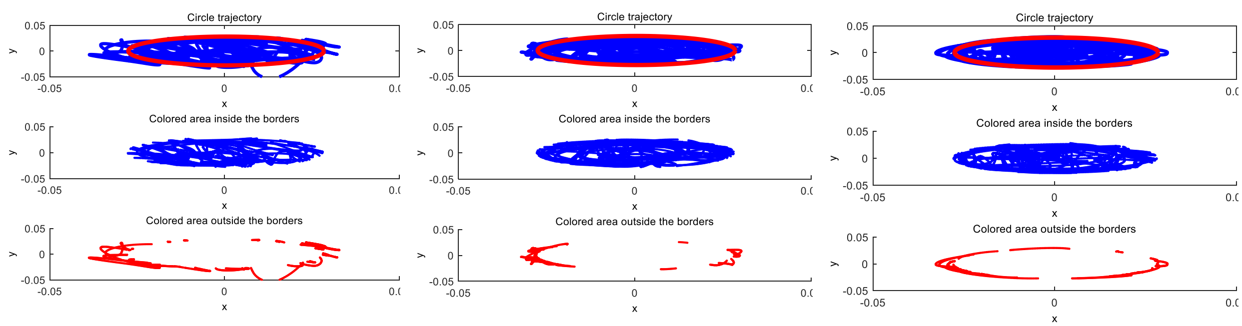

Fig. 7 Visualization of analysis of the movement trajectories of participant #1 inside and outside the ROI under No-walls (left plot), Soft-walls (middle plot) and Rigid-walls (right plot) assistance conditions

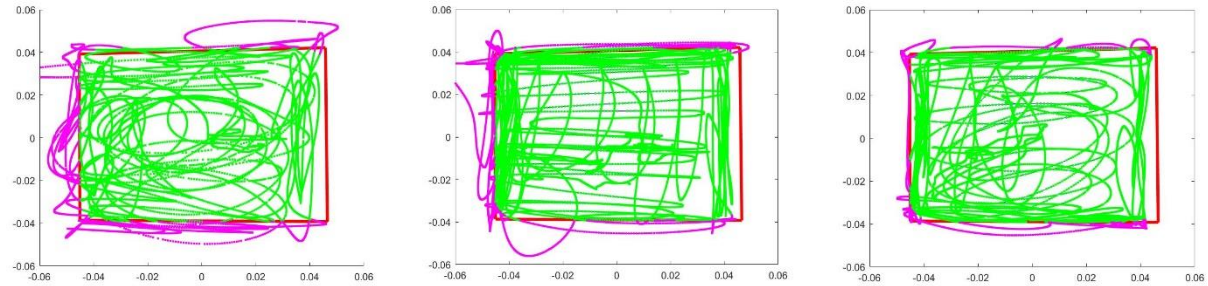

Fig. 8 Illustration of the color-coded movement trajectories of participant #1 inside and outside the ROI under No-walls (left plot), Soft-walls (middle plot) and Rigid-walls (right plot) assistance conditions

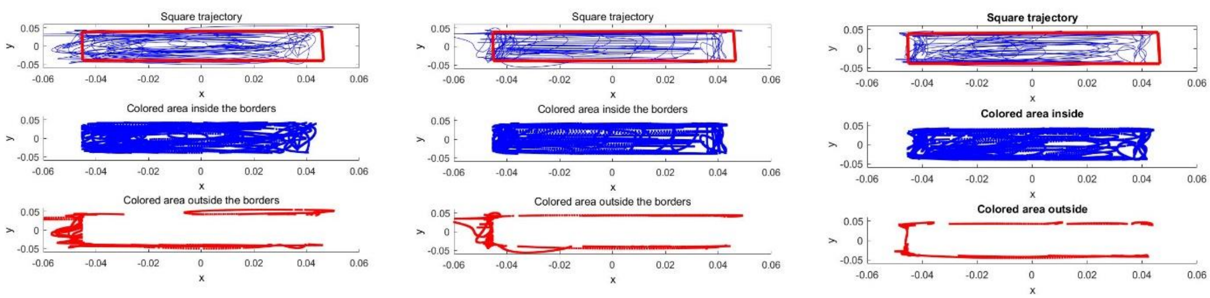

Fig. 9 Visualization of analysis of the movement trajectories of participant #1 inside and outside the ROI under No-walls (left plot), oft-walls (middle plot) and Rigid-walls (right plot) assistance conditions