A Tactile Robot for Developmental Disorder Therapy

Jeffrey L. Krichmar
Department of Cognitive Sciences
Department of Computer Science,
University of California, Irvine, CA
92697-5100 USA, jkrichma@uci.edu

Ting-Shuo Chou
Department of Cognitive Sciences
Department of Computer Science,
University of California, Irvine, CA
92697-5100 USA, tingshuc@uci.edu

ABSTRACT

Developmental disorders, such as Attention-Deficit–Hyperactivity Disorder (ADHD) and Autism Spectrum Disorder (ASD), have clinical symptoms of inattention, hyperactivity, and impulsivity. These symptoms are often accompanied by tactile and sensorimotor impairments. We introduce a CAretaker RoBOt (CARBO) to standardize and automate therapy for children with developmental disorders. CARBO is autonomous, mobile, self-contained, and focuses on tactile interactions with children. By providing a surface that encourages touch and a suite of interactive games, CARBO addresses impairments in tactile sensitivity and social interaction observed in children with developmental disorders. We conducted a small feasibility study with children having different development disorders. Children found the interactions with CARBO to be engaging for, and data CARBO recorded was sensitive to different impairments. The present study shows promising results for using CARBO as an automated form of Sensory Integration Therapy (SIT) in the future.

• Computer systems organization~External interfaces for robotics

Author Keywords

Attention-deficit/hyperactivity disorder (ADHD), Autism Spectrum Disorder (ASD), Haptics, Oppositional Defiant Disorder (ODD), Sensory Integration Therapy, Socially Assistive Robots, Tactile.

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Haptic I/O, Robotics.

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INTRODUCTION

Developmental disorders are increasingly prevalent and have a huge emotional and economic impact on families. Autism spectrum disorder (ASD) is a developmental disability that has significant social, communication and movement impairments. About 1 in 68 children have been identified with ASD according to estimates from the Center for Disease Control [1]. ADHD is estimated to affect between 3% and 11% of the population [2]. Both disorders have a huge financial impact on the economy and the families with these children. For example, the total costs per year for children with ASD in the United States were estimated to be between $11.5 billion and $60.9 billion in 2011 US dollars [3]. This significant economic burden represents a variety of costs, from medical care to special education, to lost parental productivity [4, 5].

Touch is critically important for social communication and lays the foundation for social interaction and bonding, which is often impaired in developmental disorders, such as ADHD and ASD [6, 7]. Deficits in social touch (i.e., slow, smooth strokes on the arm or face) and social interactions have been observed in autistic children [8-11]. Because these children find social touch to be unpleasant, it can lead to impairments in empathy and social behavior [12, 13].

Although there is currently no cure for these developmental disorders, intense behavioral therapy with children, such as Sensory Integration Therapy (SIT), has shown improvements in mannerisms and social function [14-17]. Moreover, parents have stated that therapy using SIT is a preferred treatment for their children [18]. SIT addresses hypo- or hyper-responsiveness to sensory input using child-directed, one-on-one play between the therapist and the child, and is used frequently to treat children with ASD [14, 15]. SIT typically involves a combination of sensory stimulation and movement, or a sensory stimulus to which the child is asked to respond [19]. The therapist guides the child through a series of activities incorporating these elements in a way that is simultaneously challenging and fun. However, the lack of standardization in SIT has been criticized [20]. Also, SIT and other therapies are labor intensive. They require caretakers, special clinics, surveys by parents, videotaping and analysis.

A novel robot design, called CARBO (CAretakerRoBOt), was developed to specifically address the movement and touch impairments seen in children with developmental disorders and to assist in standardizing SIT [21, 22]. CARBO is autonomous, mobile, and encourages interaction through touch (Figure 1). CARBO falls into the category of Socially Assistive Robots (SARs), which are increasingly being used for rehabilitation and therapy [23]. Important for developmental disorders, SARs are: 1) not as intimidating as people, 2) more socially engaging than toys or tablets, and 3) more predictable than animals. See [24, 25] for systematic studies and reviews.

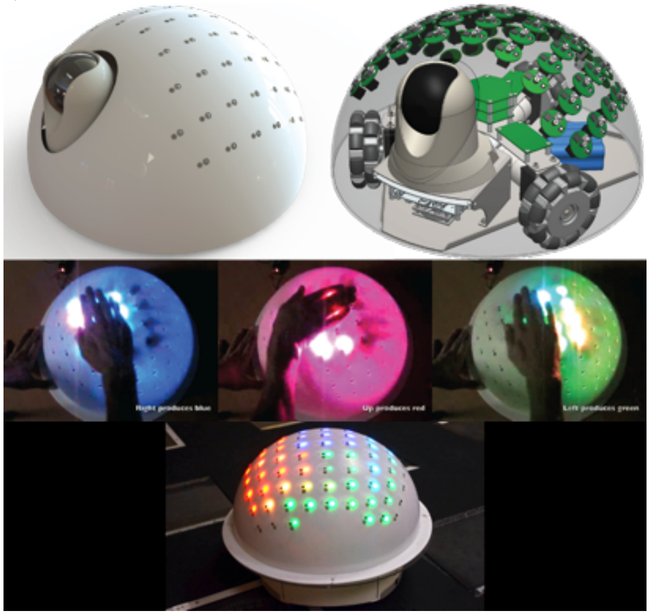

Figure 1: CARBO. Top left. Rendering shows the trackballs protruding the surface. Top right. Transparent view shows electronics, camera, and drive system. Middle. Example movements and color patterns on the prototype shell. Right movement produces blue, upward produces red, and left produces green. Bottom. The version used in the present study mounted CARBO's shell on an iRobot Create.

However, most SARs focus on eye contact, facial expression, and joint attention. They typically do not address social touch and movement impairments. One exception is the robot KASPAR, which has an artificial skin on its face. KASPAR has been shown to facilitate tactile engagement with autistic children [26-28]. Another exception is Roball [29, 30], which has been developed for playing games with autistic children. Similar to CARBO, Roball flashes colors and has panels that respond to touch. However, because both KASPAR and Roball have a limited number of binary tactile sensors spread out over a large surface area, they do not have the capability to measure stroking behavior observed in social touch. On the other hand, CARBO has an array of tactile sensors across its body that can measure the direction and velocity of hand movements.

In the present paper, we report results from a feasibility study with children having ADHD, ASD, Oppositional Defiant Disorder (ODD), and anxiety problems. Although the study was small and lacked control subjects, the children's interactions with CARBO highlighted differences specific to the children's disorder or impairment. Thus, CARBO shows promise for use in a larger, longer-term study.

METHODS

An array of trackballs, which are typically found in cellphones and other devices, was incorporated into CARBO's shell to give it a sense of touch. The trackball array can signal the direction and velocity of tactile stimuli. The robot's unique form factor encourages users to rub or pet its surface (Figure 1). The robot has LEDs co-located at each trackball, which by displaying a wide range of colors, provide visual feedback in response to touches.

The convex shell covering CARBO has an array of 67 tactile sensors and light emitting diodes (LEDs), each of which contain a circuit board with a microcontroller, red, green and blue LEDs, and a miniature trackball (Sparkfun.com COM-09308). Sweeps of a hand across the shell are coded into events that retain temporal information and allow decoding for the direction and velocity of the movement. The LEDs provide visual feedback to children when they touch CARBO. More details on the robot hardware and tactile movement decoding has been described elsewhere [22].

In the present experiments, CARBO's tactile shell was mounted on an iRobot Create platform. A laptop, which communicated with CARBO over Bluetooth, collected trackball data, controlled the LEDs on the shell, and controlled the motors and speakers on the iRobot Create. The laptop's display was also used to provide instructions and feedback to the users.

An interactive game, called ColorMe, was developed in which subjects played with CARBO, while the robot collected tactile responses (Figure 2). The game procedure was as follows: 1) an accompanying computer showed the desired color and direction of movement on CARBO's shell. 2) To finish a game, subjects were required to rub the surface of CARBO in the desired direction at a constant speed to paint the shell the desired color. 3) The robot gave auditory and motion feedback when the expected color criterion was satisfied, or when criterion was not met.

The game had six levels ranging from easy to hard. Harder levels required more complex movements and tighter movement constraints (see Table I). We use a level-5 game as an example. In the instructional phase (Figure 2A), a cartoon of CARBO was shown on the user display with three stages. Subjects were asked to paint CARBO the desired color by moving their hand in the instructed direction. For instance, in the first stage, subjects were required to paint CARBO cyan by rubbing its shell from front to back. In the second stage, a back to front movement on the left half painted the shell red. In the third stage, a hand movement along a diagonal stripe painted the shell yellow. The LEDs around each trackball only displayed a color if the hand movement was in the correct direction at the correct speed. The criterion of clearing a stage was painting 80% of the LEDs in the expected pattern of color. Progress toward a completed stage and the desired movement was provided on the display (Figure 2B). There was also auditory feedback indicating whether a move was satisfactory or not. A game was considered complete when all stages were cleared, at which time CARBO performed a happy dance by spinning left and right.

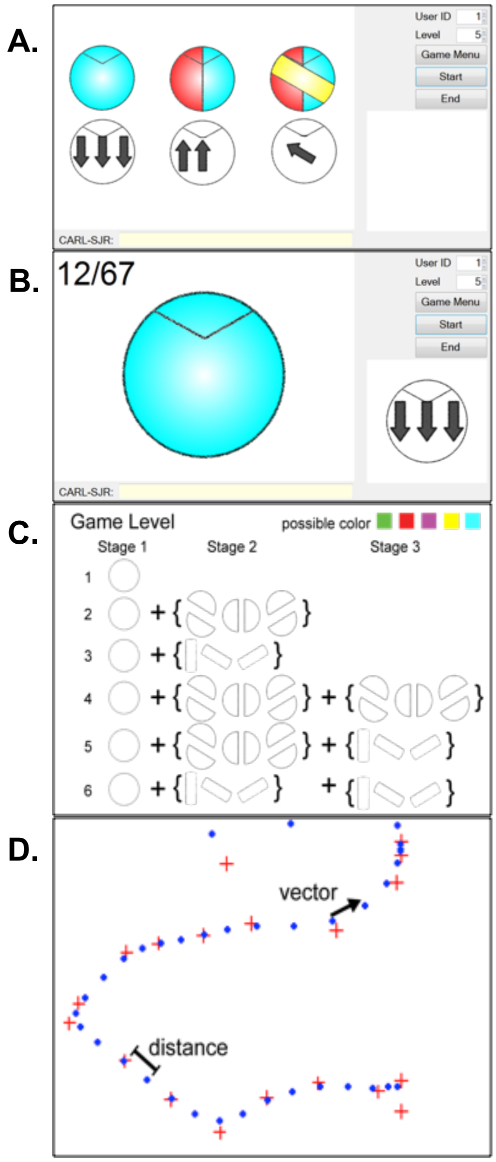

Figure 2: ColorMe Interface and configuration of each level. A. The screenshot of a level-5 game at the instructional phase. There were three stages to complete. B. Screenshot of a level-5 game at the play phase. On the right portion of the display, there is a hint for the subject to make a hand sweep in a desired direction to get the expected color. The numbers in the top left (12/67) tell the subject how many trackballs were touched and progress toward a complete stage. C. Schematic of the possible game levels. Each row indicates how many stages and the possible patterns of each level. D. Sample hand trajectory. Red crosses indicate sampled coordinates of the hand at every 120 ms. Blue dots indicate the trajectory points of a B-spline.

Figure 2C illustrates the detailed configuration of each game level. There was only one stage for level 1 as indicated in the first row. At higher levels, patterns of half circles or stripes were required. Besides more complicated patterns of color as the levels got progressively harder, the range of acceptable speeds narrowed as well (see Table I).

During game play, we recorded performance and tactile information on a nearby laptop. This included the game level, number of successful movements, wrong directional movements, overly fast movements, overly slow movements per session, and smoothness of movement.

The calculation for speed and smoothness of movements was not trivial. Because CARBO's shell is spherical, and each column of trackballs is not perfectly aligned, we needed to perform geometric corrections on the coordinates of each trackball. The bottom left trackball was mapped to the origin (0,0) while the top right trackball was mapped to (8,6). To calculate speed, we sampled the coordinates of the hand every 120ms (red crosses in Figure 2D). The coordinates of each 120ms interval were the center of trackballs that were touched. To find out the smooth trajectory of a hand, a sequence of coordinates was used to generate a B-spline (blue dots in Figure 2D). We defined the average speed of a movement to be the mean distances of all trajectory points in a B-spline and the speed variability to be the standard deviation of distances of all trajectory points [31]. We further defined the smoothness of a movement to be the coefficient of variation, which is the standard deviation of the speed divided by the mean speed. The calculation for the direction of movements was achieved by observing each pair of successive trajectory points in a B-spline to define a vector. The direction of movement was the net vector of the trajectory. With these measurements, we could set the speed tolerance for each game level and classify a movement to be correct, incorrect, too fast or too slow. Table I summarizes the speed tolerance at each level. The duration constraint set the minimum contacting duration for collecting sufficient data for calculation. Data was discarded if the duration constraint was not satisfied. However, these cases were very rare.

Table I: Speed and duration constraints for the ColorMe game.

Game Level	Speed Constraints (mm/sec)		Duration Constraint (ms)
	Min Speed	Max Speed	
1	150	1000	360
2	200	950	
3	250	900	
4	300	850	
5	350	800	
6	400	750	

RESULTS

In the present study, we collected data from 19 students at the UC Irvine Child Development School (CDS) using the CARBO robot. The CDS provides a school-based behavioral health program for children with developmental disorders and related challenges. The age of the subjects in the present study ranged from 7 to 11 years old. Diagnoses for each subject were made by the CDS clinical staff. 18 subjects were diagnosed with ADHD (ADHD). 5 of these subjects had only an ADHD diagnosis (ADHD-only). We further subdivided the ADHD group to examine comorbidity; ADHD plus ODD (ODD, n = 4) and ADHD plus anxiety (Anxiety, n = 3). The ASD group contained 1 subject with only ASD, and 5 subjects with ASD+ADHD (ASD, n=6).

Subjects played the ColorMe game where they needed to make smooth, consistent hand movements across CARBO's shell to receive positive feedback from the robot (Figure 2). Subjects started at game level 1 and needed to clear lower levels before attempting higher levels. During these games, trackball data was collected to measure performance.

The ADHD-only group showed a trend toward achieving higher game levels (Figure 3). Subjects with ODD and Anxiety disorders achieved lower levels. It should be noted that the amount of time each subject played the ColorMe game varied. Nevertheless, this data shows an interesting trend. Anecdotally, ADHD subjects wanted to be more challenged and attempted more levels. But, their movements were erratic compared to other groups. In contrast, ASD and ODD subjects had a more conservative approach and would repeat levels, which they had already completed successfully. These differences also show up in our analysis of hand movements described below.

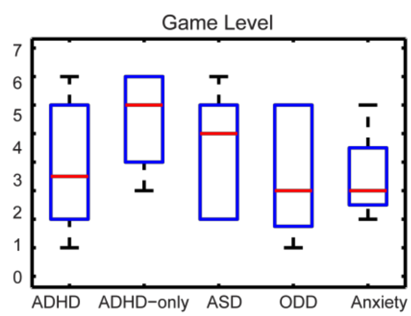

Figure 3: Highest game level achieved by the subjects. The data is grouped by diagnosis. The data is shown using a boxplot. The red line is the median value. The box shows the extent of the data from the 25th to 75th percentiles. The whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually as red plus signs (not shown in this plot).

Performance, as measured by the types of movements, varied depending on the diagnosis (Figure 4). For example, ADHD-only subjects had fewer correct moves than those subjects with ASD. Correct moves are defined as moves in the instructed direction at the desired speed, which has to be constant. Wrong moves were defined as movements in the incorrect direction. ADHD-only had the fewest wrong direction movements, but subjects with ODD and anxiety disorders had more wrong moves. Interestingly, despite having the least moves in the wrong direction, the ADHD-only group had the most hand movements that were categorized as too fast or too slow.

Depending on the disorder, we observed different hand speeds, movement variability, and smoothness of movement (Figure 5). ADHD-only subjects had faster hand movement speeds, which led to increased variability. ASD subjects, on the other hand, showed the opposite trend. Similar to ASD, ODD subjects performed slower movements with less variability. The subjects with anxiety disorders had the highest speed variability. Another way to analyze hand trajectories is to measure the smoothness of the subject's movements across CARBO's shell. If we treat a trajectory as the hand moving from a starting point to an ending point, we can measure the degree to which their hand deviates from this path by calculating the coefficient of variation. ADHD-only subjects tended toward more circuitous and discontinuous trajectories when compared to other subjects (Figure 6).

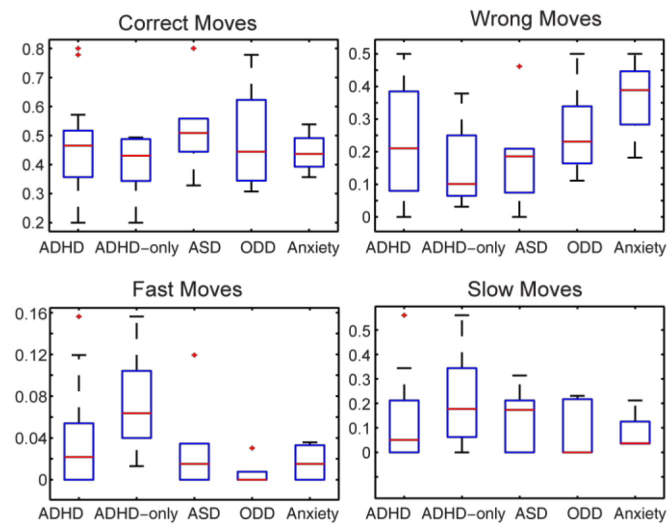

Figure 4: Hand movement performance. All movement categories were normalized by dividing the number of categorical movements (e.g., correct, or fast) by the total number of movements. Top left. Correct movements were counted as having the desired direction and speed. Top right. Wrong moves were movements in an incorrect direction. Bottom left. Fast moves were movements that were above the desired speed range. Bottom right. Slow moves were movements below the desired speed range. The boxplots denotations are the same as in Figure 3.

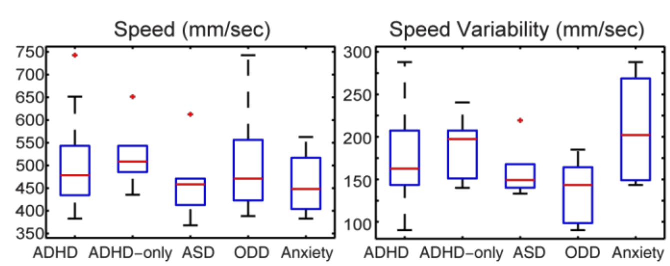

Figure 5: Speed and variability of hand movements. Left. Average speed of hand movements. Right. Variability of speed for different hand movements. The boxplots denotations are the same as in Figure 3.

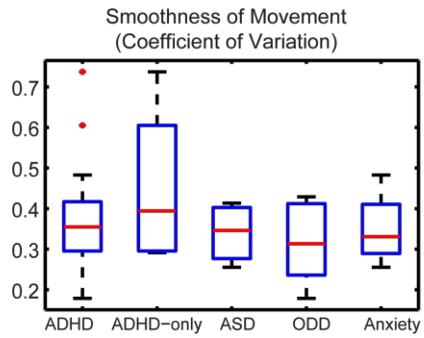

Figure 6: Smoothness of hand trajectories. The smoothness was calculated by taking dividing the standard deviation of a hand path by the average hand path. Larger values denote more circuitous and discontinuous hand trajectories. The boxplots denotations are the same as in Figure 3.

CONCLUSION

In this small feasibility study, we showed that an interactive, tactile robot has potential as a diagnostic tool for children with developmental disorders. In questionnaires and informal interviews, children expressed that the ColorMe game was interesting and intuitive. CARBO's tactile measurements were sensitive to individual differences and may have diagnostic power. Although, this needs to be confirmed in a larger study with matched typically developed children. With the development of future games and analyses, CARBO may become a SAR that focuses on the tactile impairments observed in these developmental disorders.

Although there were too few subjects to assess statistical significance, interesting trends emerged that highlight key differences in developmental disorders. For example, children with ADHD attempted and completed higher game levels, but did so with more errors, and more erratic movements. In contrast, ASD children achieved lower levels, but did so with slower and smoother movements. Children with anxiety disorders tended to make more incorrect moves than other groups and their movements were not smooth. This is encouraging pilot data for a larger study that compares children with developmental disorders to typically developing children.

Social robots may aid in diagnosis by providing consistent behavioral evaluations and standardized stimuli in diagnostic settings [23, 25]. Having a platform that can be handled and that can respond to contact has been shown to have therapeutic value [32-34]. However, this form of robot therapy is purely reactive. An interactive robot, such as CARBO, can adapt to the subject's needs or challenge the subject by playing an interactive game where the subject must learn the robot's needs or desires, and vice versa [21]. The interaction is multi-sensory. Not only does CARBO provide tactile feedback, it also provides visual, auditory and motor feedback. This fits nicely with the goals of Sensory Integration Theory (SIT), where there is interaction between the therapist and child, as well as multimodal integration [19].

The long-term goal for CARBO is to develop a therapeutic protocol for children who have developmental disorders by automating and standardizing SIT. The present study represents a first step toward achieving this goal.

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