One Dimensional Motion Tailoring for the Disabled: A User Study

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ABSTRACT

The Tailor project allows physically disabled users to provide real-time analog input to computer applications. We use a Polhemus™ tracking device and create a custom tailored mapping from each user's best range and type of motion into the analog control signal. The application is a simple video game based on *Pong*, where the analog input controls the position of the player's paddle. A group of able-bodied subjects was able to correctly hit the ball with the paddle 77% of the time, and a comparison group of children with Cerebral Palsy performed at the 50% level. More than half the disabled users were able to perform at a higher level than the worst able-bodied user.

KEYWORDS

gesture input, disabled, handicapped, user study

INTRODUCTION

The goal of the Tailor project at the University of Virginia is to allow disabled users to drive computer-based applications through the use of analog control signals. For example, with two analog control signals, one for X and one for Y, a user can smoothly move a screen cursor. Able-bodied users easily perform analog tasks, but many disabled users lack the manual dexterity to control devices such as mice and joysticks. The Tailor project recognizes that many disabled users have *some* repeatable, controllable range of motion, but that it does not correspond to any existing physical input device. Imagine, for example, an individual who could not easily move his elbow away from his waist, but could move his wrist towards or away from his chest. Such an individual is capable of generating a useful control signal, but no existing physical device exists to interpret it.

Tailor's long term goal is to generate an interface for each user which will allow him to produce real-time analog control signals with his best physical motion [Pausch90]. Our long term motivation comes from the CANDY (Communication Assistance to Negate Disabilities in Youth) project at the University of Virginia, which is an ongoing research project in augmentative communications. CANDY's overall goal is to provide a conversational speech prosthesis; a detailed description of which is beyond the scope of this paper [Pausch92, Girson]. Our initial target population is children with Cerebral Palsy (CP), but individuals with many other disabilities, such as Parkinson's, Muscular Dystrophy (MD), Multiple Sclerosis (MS) and stroke could benefit from our approach.

The class of applications we are examining consists of those that can be driven by two simultaneous analog control signals and possibly an associated on/off switch. All mouse-based interfaces fall into this category. Our approach is called *passive tracking*, a method that detects body motions by means of sensors worn by the user. We then translate the detected motion into the analog signals that drive the application. As an interim goal, we are currently producing a one-dimensional analog control signal from our users. This allows us to gain experience mapping arbitrary user motions in a simpler realm than the two dimensional case.

This paper presents both quantitative and qualitative results from our first user study, which measures how well children with CP use tailored interfaces to play a real-time video game based on the arcade game *Pong*. We use a single player game: by moving a paddle, the user attempts to keep a bouncing ball in the field of play. A player's score is a percentage computed from the number of successful blocks divided by the number of opportunities. In addition to our desire for experience with our approach, we ran this user study to demonstrate that with an appropriate input mechanism, our target population could control a real-time task such as a video game. As a benchmark, we compared how our disabled subjects did with the scores of non-disabled subjects. Our original hope was that if disabled children were provided with an appropriate input mapping, they would "not lose too badly" when compared to their non-disabled peers. In fact, the disabled children exceeded our expectations. Non-disabled subjects averaged 77% successful returns, and disabled subjects averaged 50%. More than half of our disabled subjects performed better than our worst able-bodied subject. We find this astounding, especially considering that this was the first time our subjects with CP had ever experienced this sort of interactive control.

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We begin by explaining our approach to motion mapping for one dimensional analog signals. We then describe the user study, including useful information we gained from early pilot studies. After giving a detailed presentation of the results, we discuss several issues that were raised by the performance of this user study.

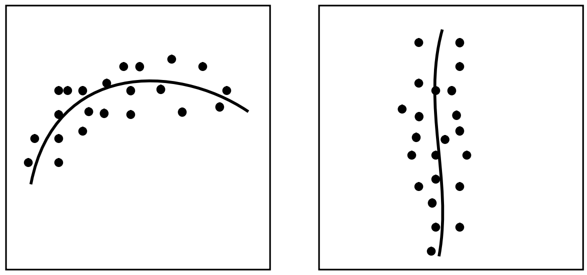
RELATED WORK ON PASSIVE TRACKING

When interfaces based on physical devices are problematic, an alternate approach is to passively track the user's body motions. The most obvious advantage of this approach is that we can tailor the interface to each individual's best range of physical motion. Another advantage is that no strength is required to move a physical switch. For the CP community, another advantage is that less coordination is required; with a physical interface, the user much first contact the device, and then move it in some way. The final advantage is that a software interface based on motion tracking can be adapted over time to account for improvement and/or fatigue.

One alternative to tracking body motion is to track eye motion. Eye-tracking is not appropriate for our application for several reasons. First, over 50% of cerebral palsied individuals have eye movement disorders [Wolraich]. Second, using eye-tracking for the long term goal of CANDY, a speech synthesizer, makes it impossible to maintain eye contact or receive visual stimulation while speaking. Third, many disabled users are poor candidates for eye-tracking because they tend to move their heads.

Gesture recognition has a long history in many contexts, but most research has focused on converting continuous body motion into discrete tokens. Two-dimensional gesture recognition has been used for printed lettering, cursive handwriting, proofreader's symbols, and shorthand notation. In all cases, the approach is to convert the continuous motion of a stylus into a discrete token as input to a language-driven computation or process. Recognition of three-dimensional gestures has also been attempted, but again the main emphasis has been on converting the body motions into discrete symbols that are interpreted as commands to the system [Bolt, Buxton]. Systems have attempted to recognize static gestures for the deaf alphabet and motions for a subset of American Sign Language. All of these approaches are based on converting three-dimensional signals into a discrete stream of tokens.

Existing work on mapping gesture into continuous control signals is extremely application dependent. For example, advanced military systems exist which map pilot head motion into weapon trajectories. The pilot's faceshield contains targeting crosshairs, and as the pilot's helmet moves with his head, the system computes the angle of his gaze [Furness]. More detailed tracking is performed in three dimensional drawing or sculpting applications [Schmandt], and virtual reality systems, where sensors attached to gloves [Foley] provide three-dimensional signals that are mapped into motions in synthetic worlds shown on traditional or head-mounted displays. These systems perform mappings from position and orientation information, but the mappings are significantly less complicated than those we propose.



User Moves Wrist
By Pivoting Elbow

User Moves Wrist
Forward and Backward

Figure 1: ***Target Curves***

MAPPING TECHNIQUE

Mapping consists of two basic phases, the collection phase and the control phase. The *collection phase* determines the comfortable and preferred motions for the user. The *control phase* performs real-time mapping of user motion based on a mapping function created from the data obtained during the collection phase. Our current mapping approach is based on *target curves*, and allows users to control a device requiring one analog input parameter. In this example, the "device" is a vertical slider on a graphical display which can be moved up and down. During the collection phase, the user is instructed to move the tracker in any manner that is comfortable, while we collect position data from the sensors. During this time, the user receives no visual or auditory feedback from the system.

For example, assume that the user had a tracker attached to a wrist, and was told to keep his hand on a horizontal table during the measurement. This effectively constrains his motion to two dimensions. Based on the on-screen display of this raw data, the therapist creates a piecewise linear curve though the data, corresponding to a dominant path of motion made by the user during the control phase. This is done by invoking a heuristic, manually specifying the curve, or a combination of both. All target curves used in this user study were manually specified. Figure 1 shows typical collection of sampled tracker data and the resultant target curves. The first user pivoted his wrist around his elbow, and the second moved his wrist forward and backward.

During the control phase, the user moves the tracker along the target curve and from his position along that curve, we generate an analog signal. One end of the curve indicates 0 percent of this signal and the other end indicates 100 percent. Intermediate positions along the target curve indicate intermediate signal values and the signal generates visual feedback on a CRT. The user is not expected to move the tracker precisely along the curve; we map tracker data to the nearest point on the target curve, as shown in Figure 2. Although in the previous example we limited the user's motions to a table surface, target curves, in general, are three dimensional.

DESCRIPTION OF THE USER STUDY

Our goal was to measure how well disabled children could control a real-time, one dimensional analog signal. While our long term goal is to drive a speech synthesizer, we chose to use visual rather than aural feedback. We could have played a tone and had our subjects play a second tone, attempting to match the pitch, but this proved unwieldy in early trials. Simple visual feedback, such as moving a slider, as shown in Figure 2, quickly bored the children. We decided to use a video game because it held the children's interest and because it made our scoring mechanism obvious.

The game was a simple variation on original arcade video game, Pong. A ball bounces off the walls of a square playing field, making a pleasant beeping noise as it contacts each wall. The player defends one of the walls, attempting to block the ball with a paddle before the ball reaches the wall. As shown in Figure 3, each child moves the paddle either vertically, defending the right wall, or horizontally, defending the top wall. On a successful defense, the ball bounces off the paddle and play continues. If the player fails to block the ball with the paddle, it reaches the wall behind the paddle and a less pleasant buzz is sounded. The game pauses for two seconds and then puts a new ball into play at the positions marked with an "X" in Figure 3. In order to avoid a lock step pattern of motion, each time the ball contacts the paddle or a wall, its angle of reflection is a slight variation of its angle of incidence.

One major advantage of using this particular video game as our task is that, although control of the paddle is one dimensional, the player needs to quickly perform

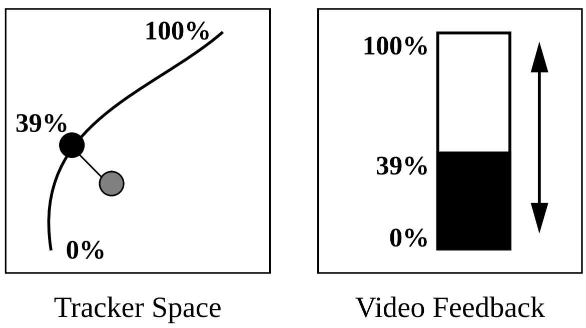


Figure 2: ***Tracker Space to Device Space. The grey dot is a user's position. The black dot is the point on the target curve closest to the current position.***

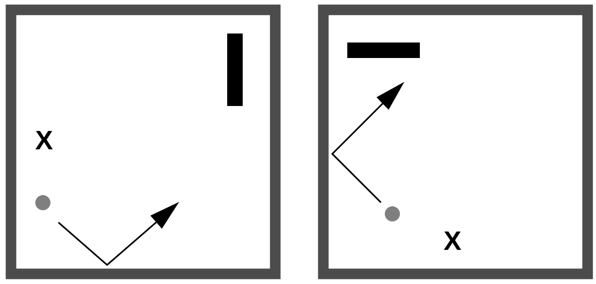


Figure 3: ***Vertical and Horizontal Games. An "X" marks the position where the ball begins.***

a two-dimensional perception and planning task in order to anticipate where to move the paddle. Many people have the incorrect impression that children with CP are all mentally retarded. While the incidence of retardation is higher in the CP population (50%-65%) [Wolraich] than in the general population, many children with CP are not retarded. By using this two-dimensional game, we make the point that our target population has the planning and cognitive skills necessary for the eventual two-dimensional version of the Tailor system.

The most difficult question was how to evaluate the effectiveness of our mappings. One design might have been to compare subjects with CP using a traditional input device such as a joystick, with a group of subjects using the Tailor system. This would have been pointless, since we know that our target population cannot use traditional input devices. What we were really interested in measuring is how well our mappings could compensate for disability; how well would a child using our system do in comparison to an able-bodied child of the same age? Therefore, we compared a group of able-bodied children to a group of children with CP who had their input mapped by the Tailor system. One problem with this approach is that if we allowed able-bodied children to use physical devices, such as joysticks, we would also be comparing the performance of the input devices involved. The Polhemus tracker is not as accurate a device as a joystick; more importantly, there is a hardware latency of approximately 85ms [Liang] which makes the game noticeably harder to play.

In order to keep the tracker lag from dominating our results, we had our able-bodied subjects use the Polhemus and Tailor-mapping software. Of course, the tailored mappings are unnecessary for the able-bodied users; they can adapt easily to any reasonable physical motion. By having both groups use the system, we discovered how big a disadvantage it is to have CP — how badly are the users disabled when we compensate by allowing them to use their best range of motion. The only remaining issue was that our able-bodied users, having grown up in Nintendo generation, clearly had practice with video games. We counter-balanced this practice effect by not allowing them to play with their dominant hand. We now suspect this had little effect, as none of our able-bodied subjects were troubled by this requirement.

Trials were run between February and September of 1991, using children ranging from age six to seventeen, inclusive. Fourteen able-bodied children and eight children with CP participated in the study. We recognize that we are using an uncomfortably small number of subjects in our analysis, but the difficulty in arranging these trials cannot be overstated. Many of our disabled subjects had to travel more than an hour by car to participate in the study. Fortunately, the distribution of results across our eight subjects is remarkably consistent, so we are comfortable reporting on the basis of our current data. Table 1 shows the breakdown of body sites used for attaching the tracker to various subjects.

attachment site	able-bodied	CP
head	2	1
Right Wrist	5	2
Left Wrist	5	5
Left Elbow	2	0

Table 1: ***Body Attachment Points***

The physical setup includes an IBM-compatible 386 personal computer with a color VGA display and either a 14 or 19 inch monitor. The playing field is a square 420 pixels on a side, and the paddle is 95 pixels wide. Our tracker is a Polhemus Isotrak™ [Polhemus]. The ball's speed was always one of three fixed values: slow = 33 pixels per second, ; medium = 64 pixels per second; fast = 178 pixels per second . With each subject, we began at the slowest speed and moved up to faster speeds as the subject became more comfortable. Three of our eight disabled subjects did not play at the highest speed.

FEEDBACK ON PILOT STUDIES

We obtained valuable feedback by running several disabled pilot subjects. The physical setup was very important for the disabled users; many have difficultly stabilizing their bodies. The Polhemus tracker cannot be used in an area with large metal objects as it is based on sensing a magnetic field, so we transferred our subjects from their wheelchairs to a specially constructed wooden chair with flexible support for seating. We believe that this may have adversely affected the performance of some of the children, as they are very dependent on the customized seating and support in their individual wheelchairs. For future trials, we will eliminate the need for this by switching to alternative tracking technologies that are less sensitive to metal [Bird]. CP is often accompanied by poor vision [Wolraich]; we acquired a large monitor and made sure that the subjects were seated close enough that they could easily see the ball and paddle.

We explained to the children that they were helping us experiment with a new device. We had originally not intended to show a running score on the screen, but our pilot subjects demanded it, and began keeping score themselves by counting. This should not have surprised us, as it is a well known phenomenon that children this age require score keeping mechanisms and invent them when they are not present.

The original game design only allowed the game to be played vertically, defending the right wall. This produced cognitive trouble for the children whose target curves were predominantly horizontal, in much the same way that rotating a mouse 90 degrees makes it almost impossible to use. Other researchers have also found that stimulus and response need to be organized in spatially similar ways [Schmidt]. What we found interesting was that the two orientations, horizontal and vertical, were sufficient.

The other things we learned during the pilot studies involved our interaction with the subjects. Having limited or no experience with video games, our subjects had trouble understanding whether they were controlling the motion of the paddle or the ball. We overcame this by having the subjects move the paddle briefly in a training session before the ball appeared. A more subtle problem had to do with retracking. The Tailor system works by using a target curve, and during a session it sometimes becomes necessary to stop play in order to establish a new target curve. This can be caused by many things, including fatigue or substantial motion of the child's body in the chair. With some subjects, when we stopped to establish a new curve they often interpreted this as a failure on their part and needed a healthy dose of reassurance before they could continue. During the trails, we took great pains to avoid the need to re-establish target curves.

RESULTS

We address first the quantitative and then the qualitative results. If all the trials had been performed with the ball traveling at the same speed, then the quantitative results would be easy to report: each subject would have successfully blocked the ball on some percentage of his trails. One could then look at the mean score for the two groups and graph their performances. The complication is that for each subject, we started them at slower speeds and then moved up when the subject felt comfortable. Subjects moved up to higher speeds quickly, but three of our eight children with CP never played at the highest speed.

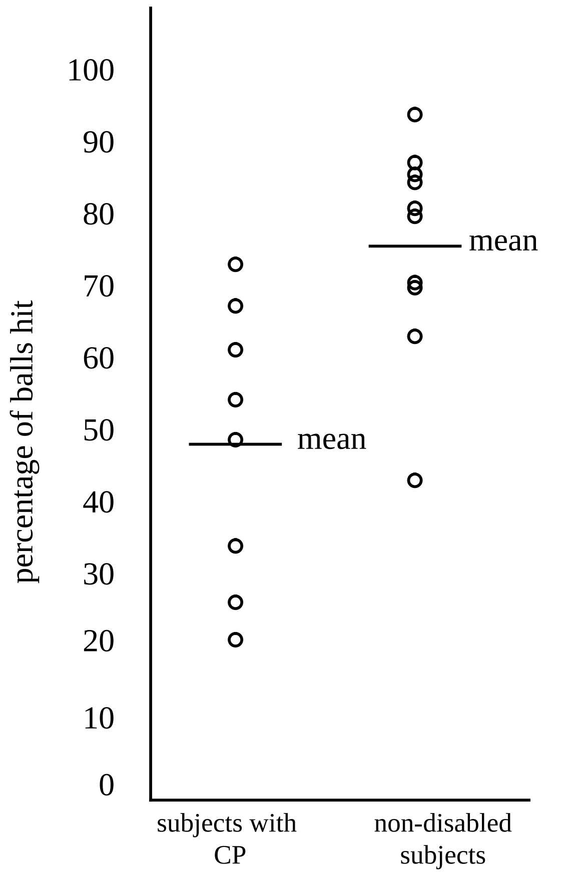


Figure 4: ***Results on Medium Speed***

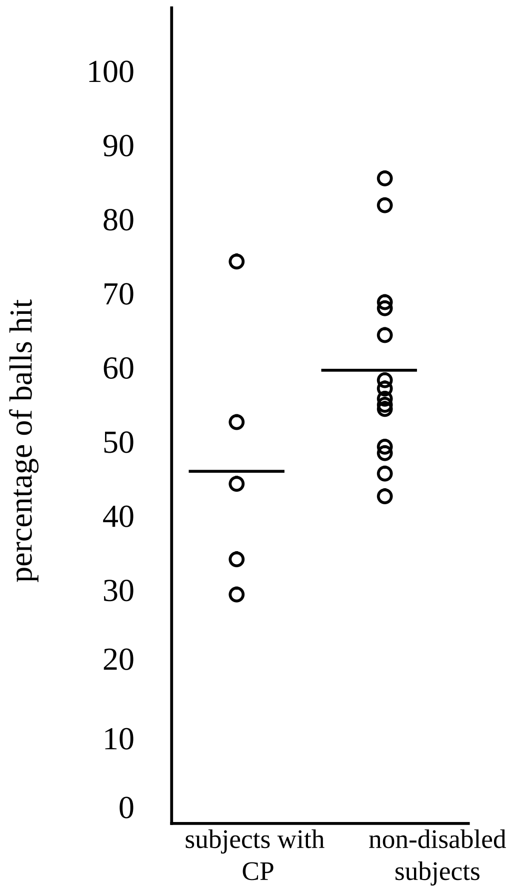


Figure 5: ***Results on High Speed***

Figure 4 shows the results of all trials run at the medium speed, the only speed for which we have data on all our subjects, and the speed upon which we base our overall quantitative result of mean performance of 77% vs. 50%. More important than the mean performance is the large overlap shown between the two groups' performances. Figure 5 shows a similar comparison of all trials run on the high speed; it is less conclusive because three of our eight subjects with CP did not attempt the high speed. Not running at a higher speed seemed to have more to do with fatigue or lack of confidence than performance. The three CP subjects who declined to try the fast speed where not our worst performers at the medium speed; they ranked 4^{th}, 5^{th}, and 7^{th} out of the 8. Therefore, we feel that there is value in ignoring the speed of the trials and lumping them together, the results of which are shown in figure 6. This lumping favors the children with CP, as they include more runs at the slow and medium speed. The full breakdown of trials by speed is given in table 2. In any reasonable interpretation of the data, it is clear that the children with CP performed better than we thought possible at this stage of the project. This is especially true given that most of our subjects had to travel to participate in the study, and several we only obtained because they were traveling to our area for clinic appointments or to have surgery at a local hospital, hardly an optimal time to participate in a user study.

For most of our subjects with CP, this is the first real-time, continuous task they had ever performed.[1] As such, it provides an interesting opportunity to observe their reactions to the pong game.

Most able-bodied subjects would anticipate where the ball was headed and then move the paddle to the correct position and wait for the ball to approach. The children with CP were much more likely to leave the paddle where it had last hit the ball, or at a particular location (near either side wall was common) and then move to block the ball at the last possible moment. We do not know why this particular motor behavior occurred. One

1. Even though half of our subjects with CP use powered wheelchairs, it is important to realize that for the CP population, wheelchair joysticks are not analog devices but are *multiway switches*. Push the stick far enough in one of four direction and the wheelchair moves. Anything less and the chair remains where it is.

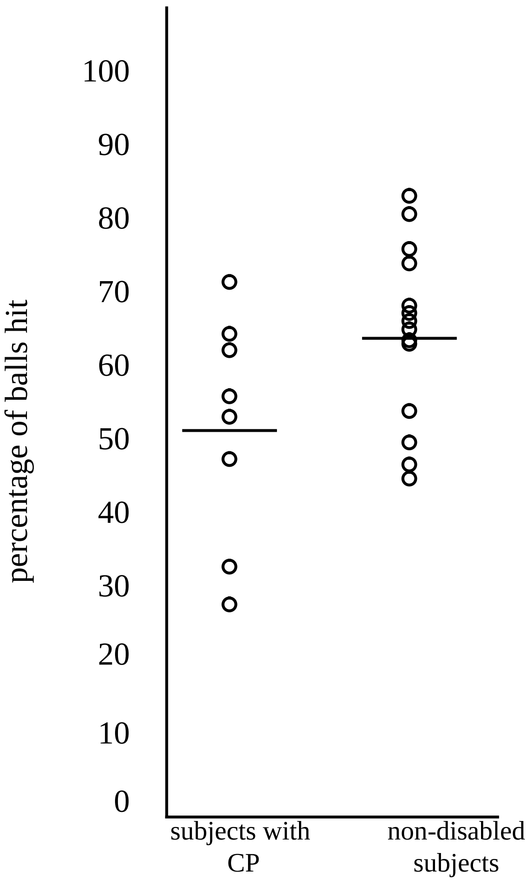


Figure 6: *Results on All Speeds Combined*

possible explanation is that the children with cerebral palsy have difficulty with response programming. More simply, they may be unable to organize and initiate muscular actions to produce a prompt motor response. Alternatively, maintaining the paddle in a “ready” position required more control at an access site [Schmidt]. The children with CP typically could not manage this, therefore returned to a consistent resting place.

None of our subjects, either those with CP or able-bodied, had a conscious awareness of the location of the target curve. This is a pleasant observation, because our eventual system will provide open-loop feedback as it is used, constantly determining the shape and location of the target curve as the device is used; the current explicit creation of a target curve is an aberration.

Our most interesting qualitative results focus on the children’s reactions to the system. Without exception, they enjoyed the trials. We are convinced that passive tracking is a good approach; although our subjects became fatigued during the trials, they continued to perform long after they would have been able to manipulate

Non-disabled Subjects

Slow		Medium		Fast	
# hit	%	# hit	%	# hit	%
0	0	0	0	33	48
0	0	34	71	35	60
0	0	25	96	28	57
0	0	26	88	33	70
0	0	0	0	35	51
0	0	0	0	36	83
0	0	21	71	28	43
0	0	19	89	36	58
0	0	0	0	35	66
0	0	27	81	36	58
0	0	35	63	37	70
0	0	29	86	41	59
0	0	36	44	28	50
0	0	33	82	33	88

Subjects with CP

Slow		Medium		Fast	
# hit	%	# hit	%	# hit	%
0	0	36	22	36	36
15	100	36	28	0	0
0	0	34	35	36	31
36	61	20	50	0	0
25	80	36	56	0	0
0	0	42	62	36	47
0	0	35	69	37	76
0	0	35	74	36	53

Table 2: *Data for All Trials*

a physical control, even one built especially for them. In addition, the mapping strategy does a terrific job at dampening out noise and jitter.

Although our eventual target population is non-vocal children with CP, in this study we included children who could vocalize to some degree so that we could get observations from them. It was from one of the children that we obtained an insight as to why passive tracking works so well. Normally, children with CP who attempt a control task “tense up” and hamper their own performance, much like a novice tennis player is often unable to swing properly until he learns to relax. We asked one of our subjects why he was able to control the paddle so well - he replied *“I’m not controlling it; it’s watching me.”* His perception was that the paddle was doing the work of following his motions, not that he was doing the work of controlling it. This difference seems to be extremely important in helping the children relax.

CONCLUSIONS

The user study we have presented is one step in a series of investigations that will be necessary to realize the long term goals of the Tailor and CANDY projects. We have now established that our mapping strategies make is possible to compensate for physical disabilities such as CP in a task requiring a real-time, one dimensional analog input.

Our results were much better than we had anticipated would be possible, especially given the adverse conditions our subjects with CP had to endure. In trials with a simple video game based on Pong, the able-bodied subjects succeeded on 77% of their trials, and the subjects with CP succeeded on 50%. Over half the subjects with CP outperformed the worst able-bodied user.

Our future efforts will be in continued enhancements to the mapping techniques used in one dimension, and in producing mappings from motion into a two-dimensional analog control signal.

ACKNOWLEDGEMENTS

We thank Ron Williams for having the vision to undertake the CANDY project. We are also grateful to Frederick Brooks, Jr. of UNC Chapel Hill, whose suggestion of videotaping the trials led to several insights. The decomposition of the two-dimensional problem into its one-dimensional components is an idea borrowed from Marc Raibert [Raibert]. Finally, we would like to thank our subjects and their families, without whose help this research would not have been possible.

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