PEDIATRIC, BIO-DRIVEN, MOBILE-ASSISTIVE DEVICES AND THEIR EFFECTIVENESS IN PURPOSEFUL DRIVING FOR TYPICALLY- AND ATYPICALLY-DEVELOPING TODDLERS

by

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ABSTRACT

Self-generated mobility is a major contributor to the physical, emotional, cognitive, psychological, and social growth and development of infants and toddlers. When young children have disorders that hinder self locomotion, their cognitive and psychological development is at risk for delay. The use of a traditional mobile-assistive device by atypically-developing infants and toddlers has shown promising results in preventing this delay, but does little to encourage the child's development of gross motor skills. The aim of this research was to develop a bio-driven mobile-assistive device—one that is controlled and driven by moving the feet in a mimicked walking gait—in order to reinforce the development of gross motor skills.

Five typically-developing subjects and one atypically-developing subject with spastic cerebral palsy were placed in the bio-driven device and instructed to navigate through a simple maze. All subjects were able to successfully complete the maze for numerous trials. Additionally, most subjects showed evidence of improved driving skill by colliding with barriers less frequently and completing the maze in shorter times in successive trials on a given testing day.

The results suggest that such a device is feasible for purposeful driving. Recommendations are given for device and protocol redesign for related future testing.

Chapter 1

INTRODUCTION

The first five years of a child's life are exceedingly important. During this time, an infant grows physically, emotionally, cognitively, psychologically, and socially. The years between toddlerhood and early childhood involve enormous neural and muscular growth. Children generally make the transition from crawling to "cruising"—a form of sidestepping while using things like furniture for support—and eventually to walking by the age of two. This movement and development of gross motor skills is crucial for a child's physical development, but has other consequences as well. The onset of infant mobility can have enduring effects on the infant's further development. As a child becomes mobile, he or she begins to develop the ability to focus visually and mentally on things outside his or her reach [1]. Self-generated mobility helps the child obtain a better grasp on orientation, coordination, space, and depth perception [2, 3, 4]. It has profound effects on a child's memory [5]. Self-generated mobility is not entirely sufficient for new psychological growth in infants, but can be necessary for building and maintaining certain skills. Prelocomotor infants provided with walkers permitting self-locomotion have shown higher levels of performance on psychological tests and an increased attention and recognition of distal objects than their peers without walkers [6, 7]. When a child becomes mobile and begins to crawl and eventually walk, he or she can begin to initiate interaction with parents, teachers, and peers, and his or her social cognition increases and drastically changes [8].

Certain disabilities and disorders have impacts on a child’s physical and/or mental development. Cerebral palsy (incidence of 2 per 1000 births) is a non-progressive physical impairment with varying degrees of severity. Spastic cerebral palsy is the most common form and can affect either one side of the body, the lower extremities, or all four extremities equally. Children with cerebral palsy are often delayed in walking development due to their damaged motor control centers and the secondary impairments of their musculoskeletal systems. Spina bifida (incidence of 1-2 per 1000 births) is a developmental birth defect resulting from incomplete closure of the neural tube. Myelomeningocele is a serious form of spina bifida, often leading to paralysis below the defect in the spinal cord. Down Syndrome (incidence of 1 per 1000 births) is a chromosomal disorder marked by trisomy of the twenty-first chromosome. Although Down Syndrome does not typically result in significant physical development impairments, the impaired cognitive abilities of Down Syndrome patients often result in children with the disorder developing motor skills much later than typically-developing children. These disorders that delay physical development in infants and toddlers can have further deleterious effects on the cognitive and psychological development of the children. In a study of infants with spina bifida, when an experimenter gained the attention of a child and asked him or her to turn and focus on a distant toy, the children tended to follow the indicated direction less frequently than infants with locomotor capabilities, signifying a lack of recognition of space beyond their personal area [9]. The research presented in this paper aims to eventually provide atypically-developing infants and toddlers with robotic mobile-assistive devices to facilitate their progress of self-generated mobility and lessen the possibility of cognitive and psychological hindrance.

Chapter 2

RESEARCH BACKGROUND

The use of power wheelchairs as assistive devices has not been widely considered by physical therapists for infants *under the age of three* [10]. For atypically-developing infants and toddlers, however, assistive-technology is often the only possibility for self-generated mobility. Using power-assistive and robotic technology in both typically- and atypically-developing infants has recently shown promising results. In a study of thirteen atypically-developing children under the age of three, it was shown that children as young as 24 months can learn to drive motorized wheelchairs [11]. A twenty month-old child with type II spinal muscular atrophy was also able to quickly learn to drive a power chair in the home independently. Additionally, the child showed improvements in the Battelle Developmental Inventory, an assessment for children through the age of seven, and the Pediatric Evaluation of Disability Inventory, an assessment of functional capabilities in children through age seven [12].

More recently, efforts have been made to incorporate mobile-assistive devices for even younger infants. When seated in a mobile robotic device without any standardized training and left to independently grasp for the controlling joystick, both a seven-month-old typically-developing infant and a fourteen-month-old infant with Down Syndrome increased their time spent in the device, the percent of time spent driving, their total path length driven, and their number of joystick activations over six different sessions [13]. The results suggested infants can associate a body action with self-generated mobility. A subsequent longitudinal experiment with a seven month-old infant with spina bifida suggests that power mobility training within the first year of life may be appropriate and highly beneficial for children with such mobility problems. The child was seen and trained with a mobile-assistive device from the age of seven months to twelve months. His driving improved significantly over the time as did his Bayley III cognition and language scores—a standard of measurements used to assess the cognitive, language, and motor abilities of children up to age three. Specifically, his Bayley scores increased at a rate greater than expected for his age [14]. Most recently, a case report quantified the effects of power mobility on classroom socialization for a three year-old with cerebral palsy with similarly promising results [15].

As a training tool for both typically- and atypically-developing children using these mobile-assistive devices, the use of force-feedback technology has been investigated. A force-feedback joystick is a joystick with motors on two axes capable of providing a force on the user's hand along those axes. Research has suggested that power wheelchairs equipped with appropriate algorithms for force-feedback joysticks can improve the driving abilities of adults [16]. Research with both typically- and atypically-developing infants and toddlers has supported similar results. Infants told to drive a specific path can learn to drive more accurately over time when using joysticks equipped with force-feedback behavior than infants without force-feedback joysticks [17].

Although this research shows promising results for the psychological, cognitive, and social development of atypically-developing toddlers, it does not directly promote their physical development. A child with cerebral palsy who obtains mobility from assistive technology using a joystick may be discouraged to advance his or her own walking abilities through physical therapy. The aim of the current research presented here is to develop a "bio-driven" mobile-assistive device—one that encourages children to develop gross motor skills by reinforcing large physical movements. It is believed that such a device will eventually show similar promising results in the psychological, cognitive, and social development of atypically-developing toddlers while additionally showing less hindrance of physical development. Additionally, such a device may have positive impacts on bone health, kidney function, and cardiopulmonary function over time. This research focuses on a bio-driven walking design—one that will incorporate an infant or toddler mimicking a walking gait while standing atop a robotic device for generating motion.

Chapter 3

DESIGN CONSIDERATIONS

3.1 The robot

The mobile device used in this research is a robot provided by MobileRobots, Inc. MobileRobots is a company responsible for mobile robotic systems with either autonomous or user-dependent capabilities. The model used for this research is a Pioneer 3-DX, a two-wheeled model with an additional caster wheel for support. The robot comes equipped with sixteen sonar sensors and eight bumpers, arranged in a ring around the robot, and an optional range-finding laser, which can be used for obstacle detection. An onboard computer runs the Windows XP operating system. The robot platform is controlled by the Advanced Robotics Interface for Applications (ARIA), an object-oriented application interface written in C++ programming language. Using the ARIA library, one can define user tasks to incorporate with the operations of the onboard computer for controlling the robot.

The robot is driven by the motion of the two wheels. The wheels are located on the same axle but are capable of rotating independently. The maximum translational speed of the robot is approximately 4.6ft/sec and the maximum rotational speed is approximately 5.24rad/sec. The Pioneer 3-DX model is shown below.

Figure 1 Pioneer 3-DX robot provided by MobileRobots, Inc.

3.2 Stability concerns for a standing design

Because of the nature of this experimental setup, with a toddler standing upon the robot, support aids were constructed and attached to the sides of the robot. Using anthropometric data assembled by Snyder, et al, sponsored by the Consumer Product Safety Commission under contract by the Food and Drug Administration, the center of gravity and height of an average three-year-old are 29.70in and 36.65in from the ground, respectively [18]. Although this Pioneer 3-DX robot model has been used for previous research using seated children, the center of gravity of an average three-year-old is raised approximately 13.5in from a seated position to a standing position, requiring the footprint of the robot to be extended in order to increase stability and prevent tipping. Additional running supports and caster wheels were constructed and attached to the sides of the robot. The weight of the robot is reported by MobileRobots, Inc. as approximately 19.84lbs and the height as approximately 9.33in. The center of gravity of the system including the robot and a child standing upon the robot measured from the ground is reported below for the average-sized one, two, and three year-old. Using this data, a "worst-case" radius for the caster wheels on the additional supports was calculated—the minimum distance from the center of the robot the additional caster wheels should be placed for safe support, and calculated by assuming a child on the robot was leaning as far as possible to one side.

Table 1 Design specifications for constructing additional stability supports

	Weight (lbs)	Absolute center of mass (in)	Worst case radius (in)
Pioneer 3-DX	19.84	4.67	
One year-old	20.28	16.73	
Two year-old	26.01	19.17	
Three year-old	29.76	21.70	
DX + one year-old	40.12	15.48	8.46
DX + two year-old	45.86	18.19	10.88
DX + three year-old	49.60	20.48	13.02

Using this data, the additional supports were constructed using pieces of 2x3 lumber with caster wheels at four points located approximately 13in from the center of the robot. The Pioneer 3-DX robot with the additional supports is shown below.

Figure 2 Pioneer 3-DX with additional stability supports

3.3 Standing board design

A design was then constructed to support a child in a standing position upon the robot. A standing board was constructed from lumber and plywood, given the limited payload of the Pioneer 3-DX model. A playground swing chair was attached to the standing board with nylon ropes and secured through the use of cleats. The chair is height adjustable to cater to children of approximately 39in, the 95th percentile height of three year-olds, and able to be modified to support all, some, or none of the child's weight, depending on the desired experimental situation and abilities of the child tested. The DX model can withstand a payload of only 55.12lbs, which includes the weight of the standing board and the child. With this consideration, a standing board was constructed with the goal of a lightweight but strong design. The result was a 20.1lbs standing design capable of supporting a 35lbs child—approximately the average weight of a four year-old or the 95th percentile weight of a thirty month-old. The design was tested to 60lbs with no visible deflection or deformation, giving an absolute minimum factor of safety of 1.71 for a child weighing the maximum 35lbs. The standing design is shown below. Fleece and felt fabric were added to the standing board and chair in order to make the design more comfortable and more enjoyable for children.

Figure 3 **Full standing design for Pioneer 3-DX robot**

3.4 Control mechanism

In past research, the infant and toddler robots have been driven with a joystick. In order to make this design “bio-driven”, a new control mechanism that involves mimicking a walking gait was necessary for controlling the robotic motion. The movement of the child’s legs and feet should signal the robot to move. Considering the cost, weight, and space constraints concerned with the robot, a camera and marker system was decided upon. A web camera placed underneath the swing chair can track the motion of three-inch by three-inch square markers attached to each of a child’s calves. When the camera recognizes motion of the markers, a signal is sent to the robot to cause forward motion with a speed proportional to the speed of the legs and feet. Rotational motion and turning is controlled by a joystick situated on a small table in front of the child. Thus, forward motion is controlled by leg movement and turning by joystick motion controlled by hand and arm motion.

3.4.1 Augmented Reality Software

Under usual circumstances, multiple cameras are required for triangulating the three-dimensional spatial position and orientation of a marker. When using “augmented reality” software, however, only one camera is required to accurately report the three dimensional position of a specialized marker. Augmented reality is often used for virtual reality applications, when three-dimensional graphics need to be added to video in “real-time”—at the actual time the video is being processed. By using a camera that is calibrated to a computer and specialized markers that are recognized by the software, three-dimensional position and orientation of multiple markers can be processed simultaneously in real time.

ARToolKit is a software library that was developed by Dr. Hirokazu Kato and is used for augmented reality applications. ARTag is a similar software library, developed in 2004, with greater capabilities than those of ARToolKit. Although ARToolKit can process images faster than ARTag when using a small number of markers, as is the case with this research, ARTag can recognize markers much more easily than ARToolKit if part of the marker is obscured from view. With this consideration, ARTag software was chosen for this research because of its ability to more convincingly track partially-obscured markers. Examples of the style of markers used by ARTag software are shown below.

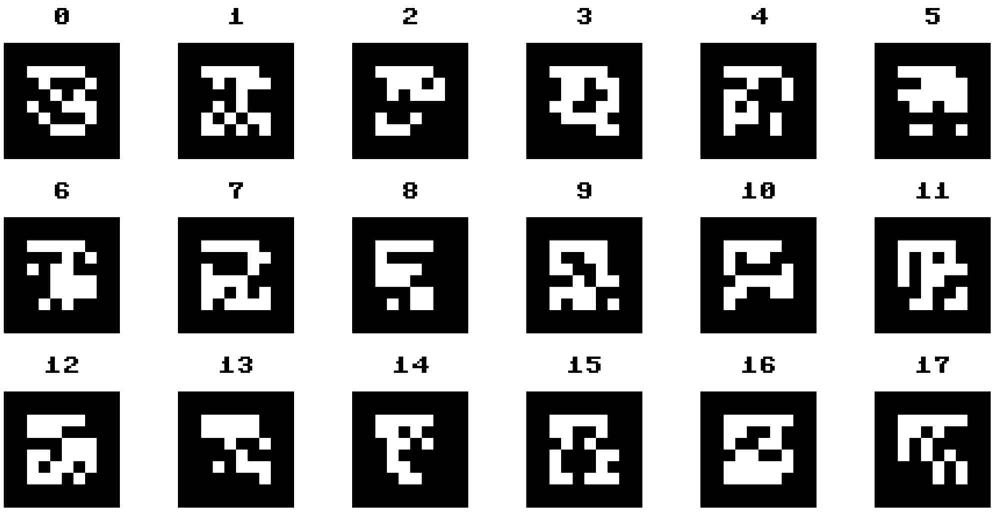


Figure 4 Examples of eighteen ARTag markers

There are two thousand two markers in the ARTag library. As seen above, each marker has a specific number recognized by the software. Two markers were chosen from the library and used for this research based on preliminary tests for usefulness and effectiveness. One marker was attached to each of the child's calves using Velcro straps.

3.4.2 Marker velocity approximation

The velocity of the robot was linearly proportional to the velocity of the child's feet, i.e. as the child moves his legs and feet more and faster, the robot moves faster, reinforcing the gross motor skill. The augmented reality software cannot directly track the velocity of a marker, only the position. As a result, the velocity of each marker must be approximated. If the successive positions of a marker are numerically differentiated, an approximation for the marker velocity can be obtained. The velocity at a certain point in time can be approximated by previous positions through finite difference theory. A backward difference approximation using the current position, x_i, and two previous positions, x_{i-1} and x_{i-2}, can approximate the velocity as follows:

$$f'(x_i) = \frac{3f(x_i) - 4f(x_{i-1}) + f(x_{i-2})}{2\Delta t} + O(\Delta t^2) \tag{1}$$

where Δt is the spacing between x_i and x_{i-1} and $O(\Delta t^2)$ is the approximation error of order Δt^2.

AMCap is a software for capturing video from a webcam. With the AMCap software, the user can manually adjust exposure settings for a camera being used. Using the AMCap software, the camera captures the position data once every 1/120 sec (0.00833sec), so the velocity of the robot is essentially updated in real time. An error of second order with $\Delta t = 0.00833$ is acceptable for this application within the processing limitations of the robotic onboard computer. The velocity of each marker is approximated at each time interval. The values are modified using a low-pass filter to rid the data of any extraneous noise. A threshold velocity was set for each marker individually. Only marker velocities above the threshold value cause forward robotic motion. This reduces the chance for unintended and accidental robot movement. When the child moves his or her feet and the markers, the larger of the two marker velocities is sent to the robot and scaled appropriately as a velocity command.

Chapter 4

RESEARCH METHODS

The objective of this research was to determine whether or not toddlers can learn to drive a bio-driven mobile-assistive device purposefully and improve their driving skills over time. Five typically-developing toddlers, aged thirty-four to thirty-nine months, four of whom were involved in previous related research, and one atypically-developing toddler with spastic cerebral palsy, aged forty-nine months, were seen at the University of Delaware's Early Learning Center, located at 489 Wyoming Avenue, Newark, Delaware. Prior to beginning this research, parents of children signed an informed consent that was approved by the University of Delaware Human Subjects Review Board.

The toddlers were shown and placed in the robot and verbally explained and physically shown how the robot functions. The children were asked to complete a simple maze with barriers constructed from foam wedges as quickly as possible. A researcher stood at different junctions of the maze and verbally encouraged the children to complete the task. A birds-eye model and a floor-level view of the maze are shown below. The start and finish points are represented by a star. A researcher stood at the positions indicated by the triangles to encourage the child to complete the path. The subjects were trained to drive back and forth through the maze.

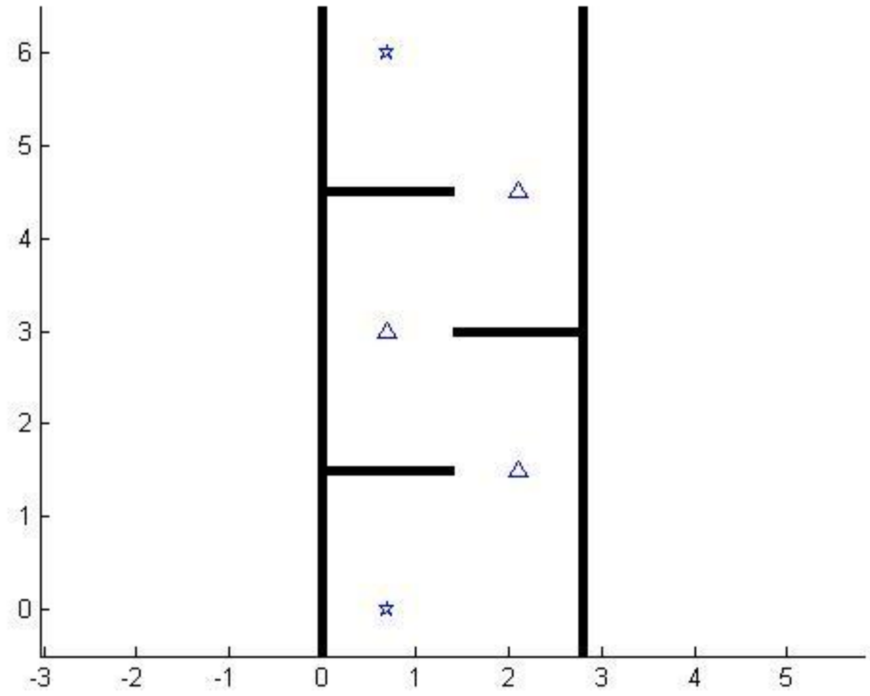


Figure 5 Birds-eye model of maze.

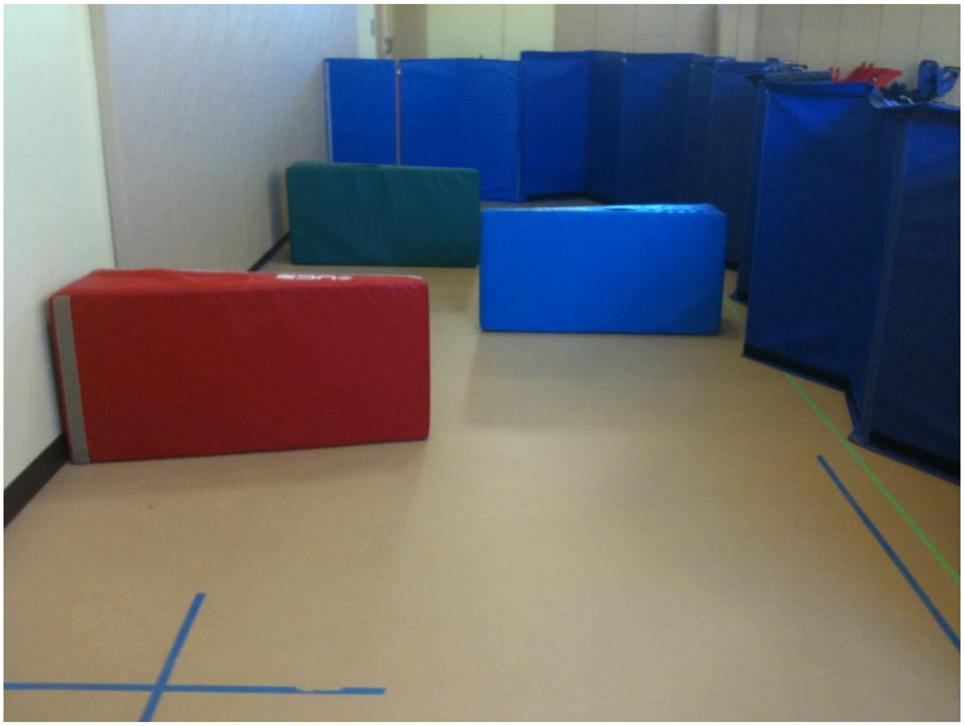


Figure 6 Photograph of maze from floor level

The robotic onboard computer recorded position and time data every tenth of a second. The path followed by the subjects was plotted for each trial. For the trials which the subject returned back through the maze, the position plots were reflected about the y-axis for easier visual comparison. The time to completion was also recorded and analyzed for each trial. A total of six trials were recorded for each typically-developing subject and ten trials for the atypically-developing subject over the course of several visits. The number of trials completed per day was dependent on the child's tolerance of time on the robot each day. When a toddler announced that he or she was finished, he or she was taken out of the device and trials were continued on another day.

Two hypotheses were formed at the beginning of the experimentation. First, it was anticipated that the subjects would show an increase in driving coordination and skill as their number of completed trials through the maze increased. To measure this, the occurrence of collisions with the barriers or walls was noted. Second, it was anticipated that the subjects would exhibit an increase in trial completion speed over time. It was believed that the time required for maze completion would decrease approximately linearly with the number of trials completed, indicating an increase in driving ability and skill and also skill retention between different testing days.

Chapter 5

RESULTS AND DISCUSSION

5.1 Typically developing subjects

The five typically developing toddlers were tested for six trials each. Subjects 1, 3, 4, and 5 were tested in earlier related mobile robotics experiments. Subject 2 was not included in any earlier experiments.

5.1.1 Results from Subject 1

Subject 1 was a thirty-four month-old male subject. The path for each trial was logged by the onboard computer. The plots for Trial 1, Trial 3, and Trial 5 were mirrored about the vertical axis for easier visual comparison, as explained above. Trials 1 and 2 were completed on the same day. Trials 3 and 4 were completed one week later. Trials 5 and 6 were completed nine days after that.

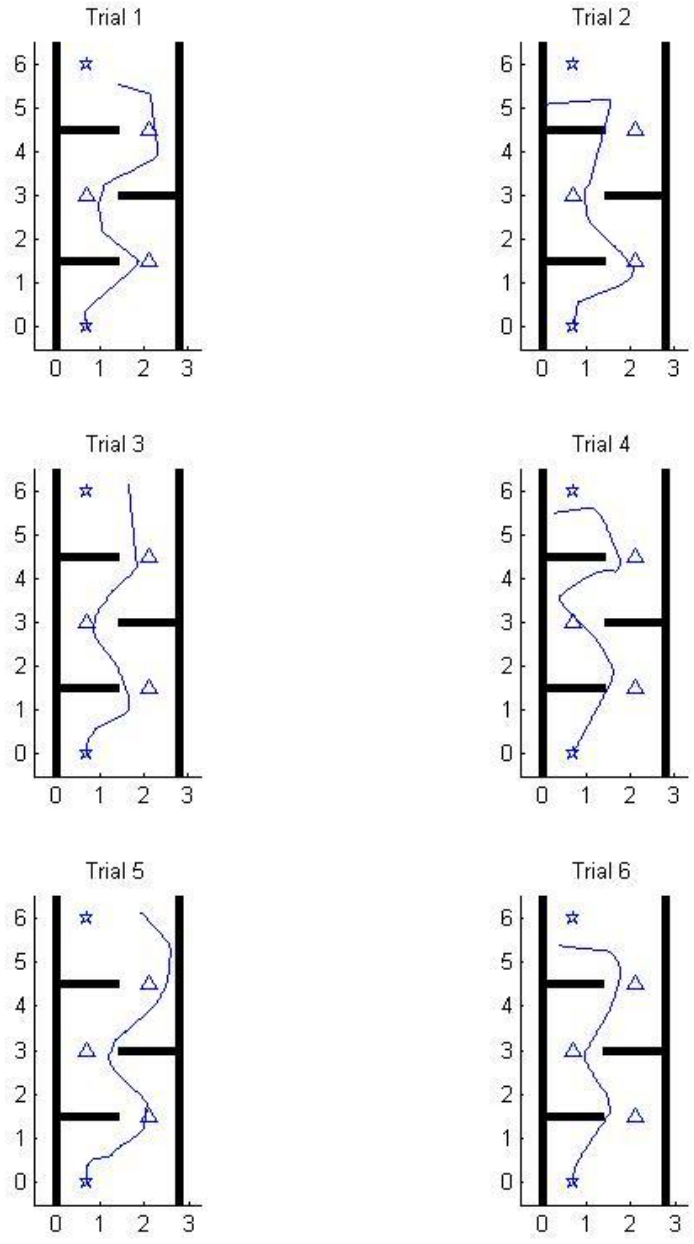


Figure 7 Plots of paths taken by Subject 1 for each trial

Subject 1 successfully completed six trials of the maze. During Trial 2, Subject 1 collided with the third barrier and it had to be moved out of the path of the robot. Additionally, the subject collided with the wall near the final goal. During Trials 4 and 6, the subject lightly collided with the edge of the first barrier, but was able to successfully navigate around the first and subsequent barriers and end within one meter of the final goal. The subject was able to navigate past the third barrier in all six trials. The deviation from the final intended goal for each trial is shown below.

Table 2 Deviation from final intended goal for each trial completed by Subject 1

Trial number	Deviation from goal (feet)
1	2.759514
2	3.699147
3	3.143045
4	2.136483
5	4.024934
6	2.312008

The time data for each trial completed by Subject 1 is found below.

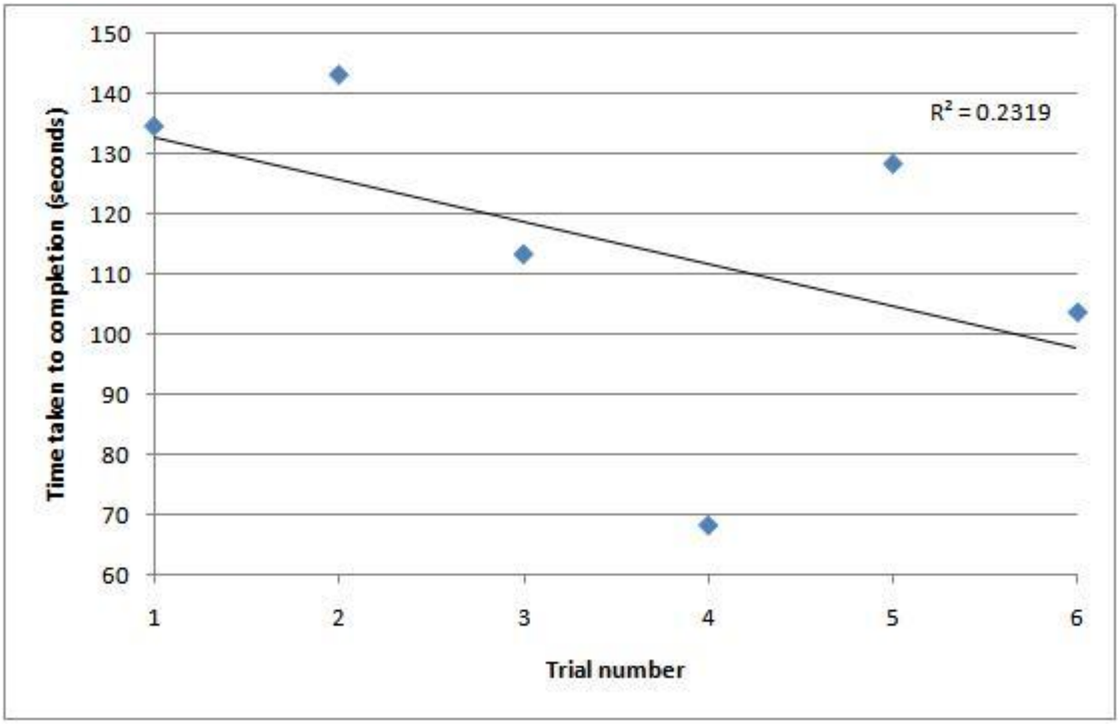


Figure 8 **Time taken for each trial versus trial number for Subject 1. Line of best fit shown with correlation coefficient of 0.2319.**

The trial times for Subject 1 varied from 68sec to 143sec. It was hypothesized that the subject would show a linear decrease in time per trial as the number of trials increased. It cannot be argued that there was a linear relationship between the time and trial number with such a weak correlation coefficient of 0.2319, but it can be supported that the subject did exhibit a general trend of decrease in time as the number of trials progressed, as the line of best fit displayed a negative slope.

Although the overall trend did not show a strongly linear relationship, it is useful to consider the time between each pair of trials. Trials 1 and 2, on the first day of testing, were the slowest trials for Subject 1. This is as expected, since this was the first day the subject was introduced to the new robot and control mechanism. On the second day of testing, the time taken for both trials was less than the previous week's trials, and Trial 4 took less time than Trial 3, as anticipated. On the third day of testing, the subject began with a trial sixty seconds longer than the previous trial from nine days before. The second trial from the final day, Trial 6, took shorter than Trial 5, as expected. Although this trend was similar to that exhibited from Trials 3 and 4, the subject did not show very strong overall retention of driving skill from week to week, resulting in the weakly linear trend over all six trials. It is possible that the trend would be stronger, and the driving ability retention greater, had the trials been taken over successive days instead of with seven or nine days between pairs of trials.

5.1.2 Results from Subject 2

Subject 2 was a thirty-nine month-old male. The path for each trial was logged by the onboard computer. The plots for Trial 2, Trial 4, and Trial 6 were mirrored about the vertical axis for easier comparison. Trials 1, 2, and 3 were completed on the same day. Trials 4, 5, and 6 were completed twelve days later.

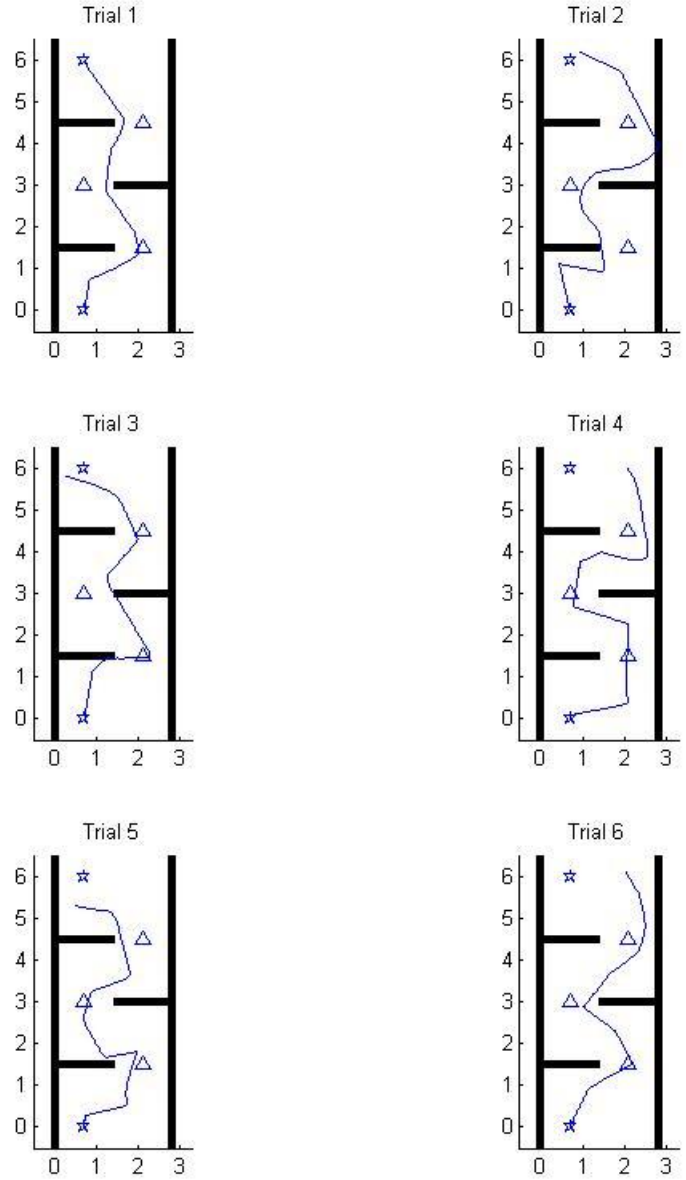


Figure 9 Plots of paths taken by Subject 2 for each trial

Subject 2 successfully completed six trials. During Trial 2, Subject 2 collided with the edge of the first barrier, but was able to successfully navigate around it. Additionally, the subject collided with the wall after navigating around the second barrier. During Trial 3, the subject collided with the first and second barriers, the first of which had to be moved out of the path of the robot. The subject was able to navigate past the third barrier in all six trials. The deviation from the final intended goal for each trial is shown below.

Table 3 Deviation from final intended goal for each trial completed by Subject 2

Trial number	Deviation from goal (feet)
1	0.56332
2	0.981299
3	1.536089
4	4.572507
5	2.445538
6	4.425525

The time data for each trial completed by Subject 2 is found below.

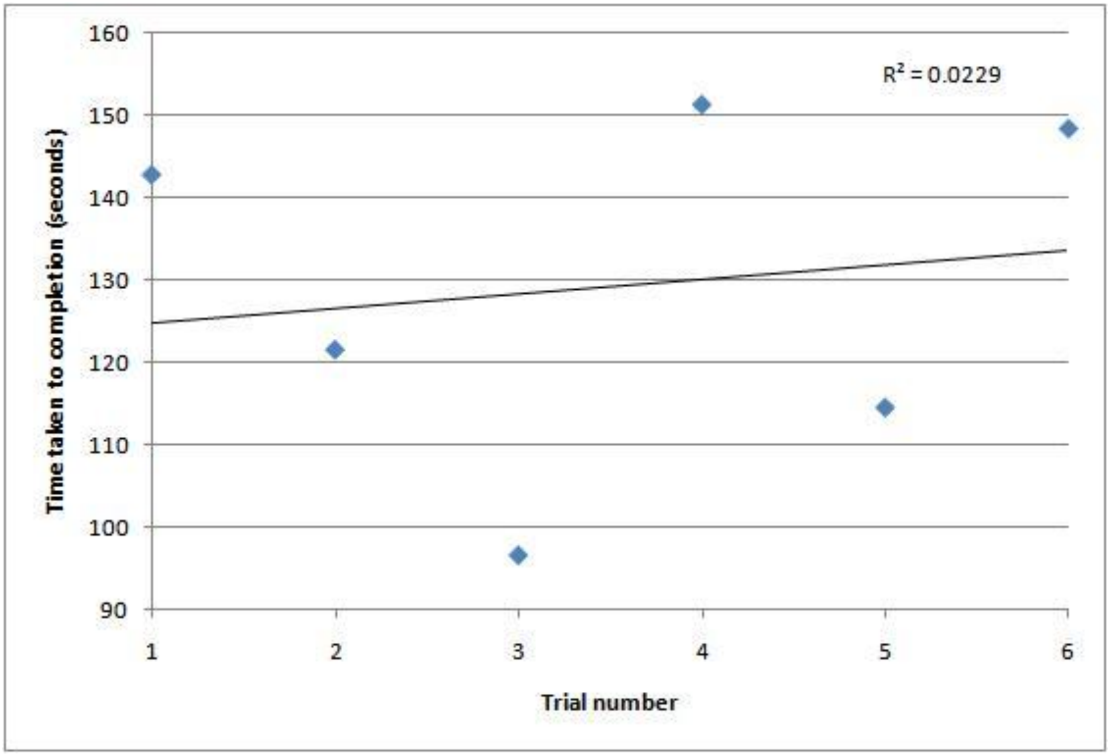


Figure 10 Time taken for each trial versus trial number for Subject 2. Line of best fit shown with correlation coefficient of 0.0229.

The times for Subject 2 varied from 97sec to 151sec. It was hypothesized that the subject would show a linear decrease in time per trial as the number of trials increased. It cannot be argued that there was a linear relationship between the time and trial number with such a very weak correlation coefficient of 0.0229. Additionally, the trend actually showed an increase in time to maze completion as the subject completed more trials, which is contradictory to what was expected.

Although the overall trend did not show a decreasing linear relationship, it is useful to consider the time between each pair of trials. Trials 1, 2, and 3 were completed on the same day. These trials showed a strong trend in decreased time with increase in trial number. The trend is shown below.

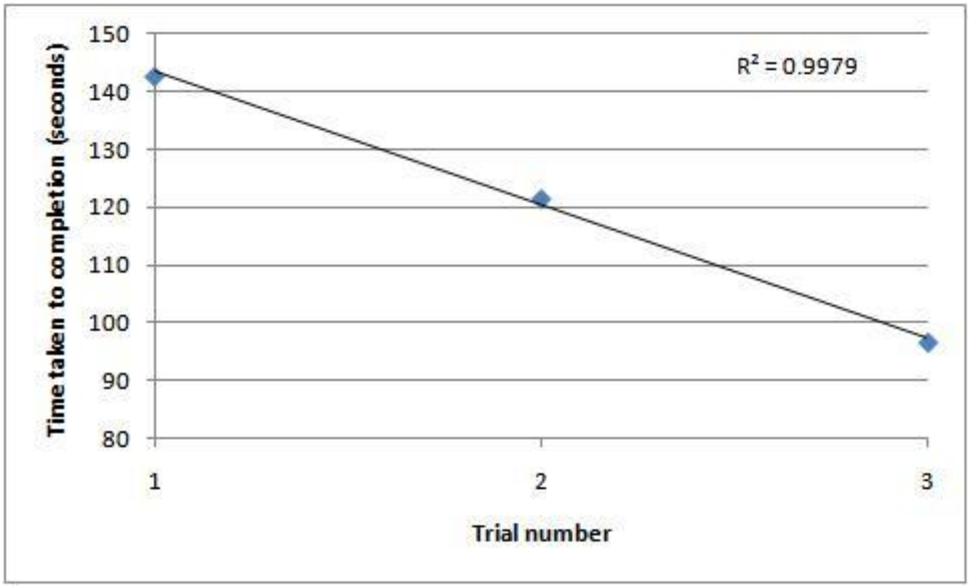


Figure 11 **Time taken for each trial versus trial number for the first day of testing for Subject 2. Line of best fit shown with correlation coefficient of 0.9979.**

The three trials from the first day of testing show a very strong decreasing linear relationship with a correlation coefficient of 0.9979, as hypothesized. Although the hypothesis cannot be fully supported, considering these data include only three trials, this trend shows an initial support for a correlation between time taken for each trial and number of trials taken.

Unfortunately, this trend is not seen from the second day of testing. Like Subject 1, Subject 2 did not show very strong retention of driving skill from week to week; the first trial from the second day of testing, Trial 4, took considerably longer than the final trial from the first day of testing, Trial 3. Additionally, the final trial completed by Subject 2 took thirty-four seconds longer than the previous Trial 5. This does not support the hypothesis that the subjects would exhibit a decrease in time to completion as the number of trials completed increased. Despite these data not supporting the hypothesis of a decrease in driving time over multiple trials, Subject 2 was able to successfully complete six trials through the maze.

5.1.3 Results from Subject 3

Subject 3 was a thirty-eight month-old female. The path for each trial was logged by the onboard computer. The plots for Trial 1, Trial 3, and Trial 4 were mirrored about the vertical axis for easier comparison. Trials 1, 2, and 3 were completed on the same day. Trials 4 and 5 were completed seven days later. Trial 6 was completed another seven days after that.

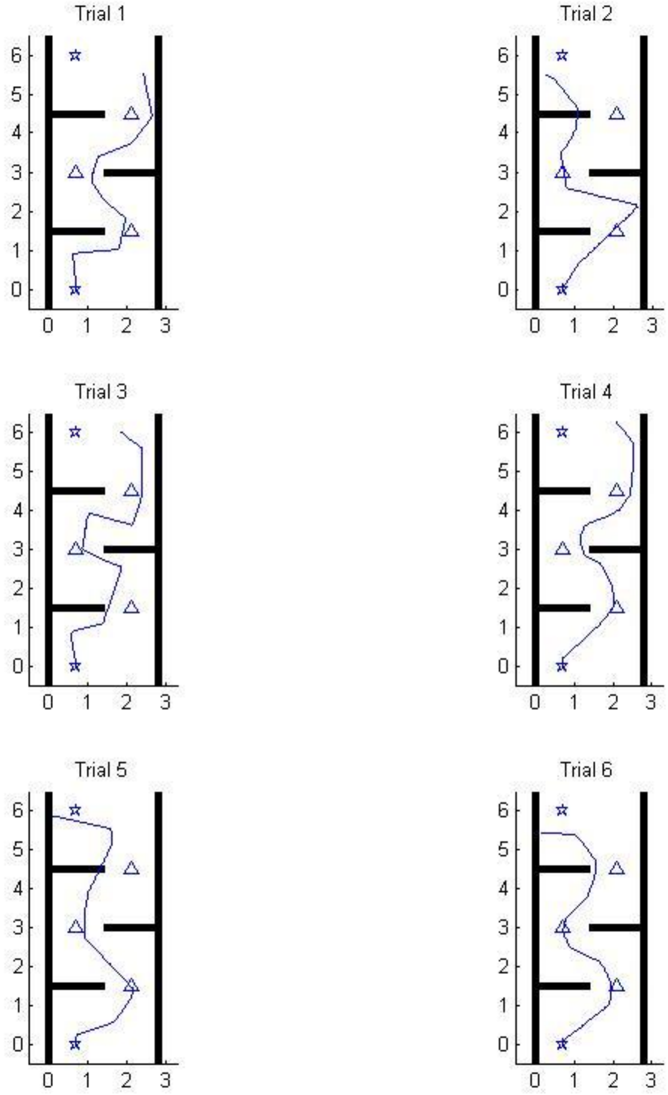


Figure 12 Plots of paths taken by Subject 3 for each trial

Subject 3 successfully completed six trials. During Trial 2, the subject collided with the third barrier and it had to be moved out of the way of the robot. During Trial 5, the subject collided with the third barrier, but was able to navigate around it. The subject was able to navigate past the third barrier in all six trials. The deviation from the final intended goal for each trial is shown below.

Table 4 Deviation from final intended goal for each trial completed by Subject 3

Trial number	Deviation from goal (feet)
1	5.872047
2	2.213911
3	3.801181
4	4.623032
5	1.988845
6	2.502953

The time data for each trial completed by Subject 3 is found below.

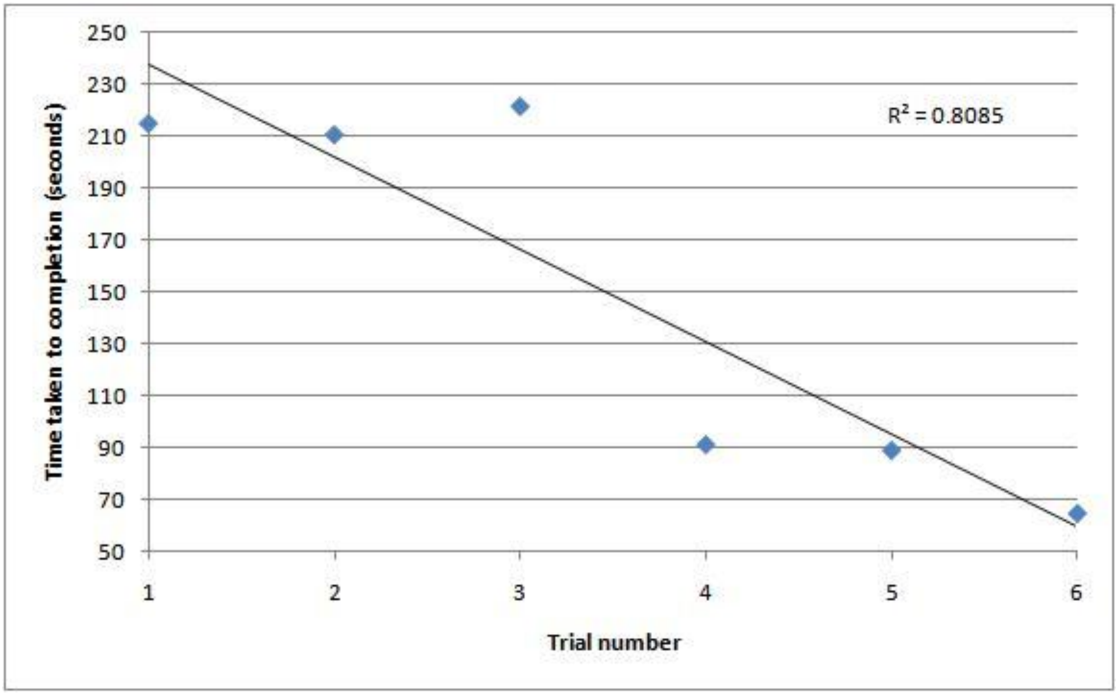


Figure 13 **Time taken for each trial versus trial number for Subject 3. Line of best fit shown with correlation coefficient of 0.8085.**

The times for Subject 3 range from 64sec to 221sec. The six trials for Subject 3 exhibit a fairly strong linear relationship with a correlation coefficient of 0.8085. This supports the initial hypothesis for the experiment.

Additionally, it is useful to consider when the trials were completed. Trials 1, 2, and 3 were completed on the first day of testing. Subject 3 completed these three trials with similar times of 214sec, 210sec, and 221sec, respectively. Trials 4 and 5 were completed one week after the first three trials. Subject 3 showed some retention of driving ability and the times for these two trials dropped drastically by approximately two minutes to 91sec and 90sec, respectively. On the final day of testing, Subject 3 continued to show retention of ability and the time to completion of

Trial 6 dropped by another thirty seconds to 64sec. These data support the belief that a child's driving skill will improve over time as they spend more time in and become more familiar with the robot. For each day of testing, Subject 3 showed consistent times for each trial and was able to improve upon those times on the next day of testing.

5.1.4 Results for Subject 4

Subject 4 was a thirty-eight month-old female. The path for each trial was logged by the onboard computer. The plots for Trial 1, Trial 3, Trial 4, and Trial 6 were mirrored about the vertical axis for easier comparison. Trials 1, 2, and 3 were completed on the same day. Trials 4 and 5 were completed eleven days later. Trial 6 was completed another three days after that.

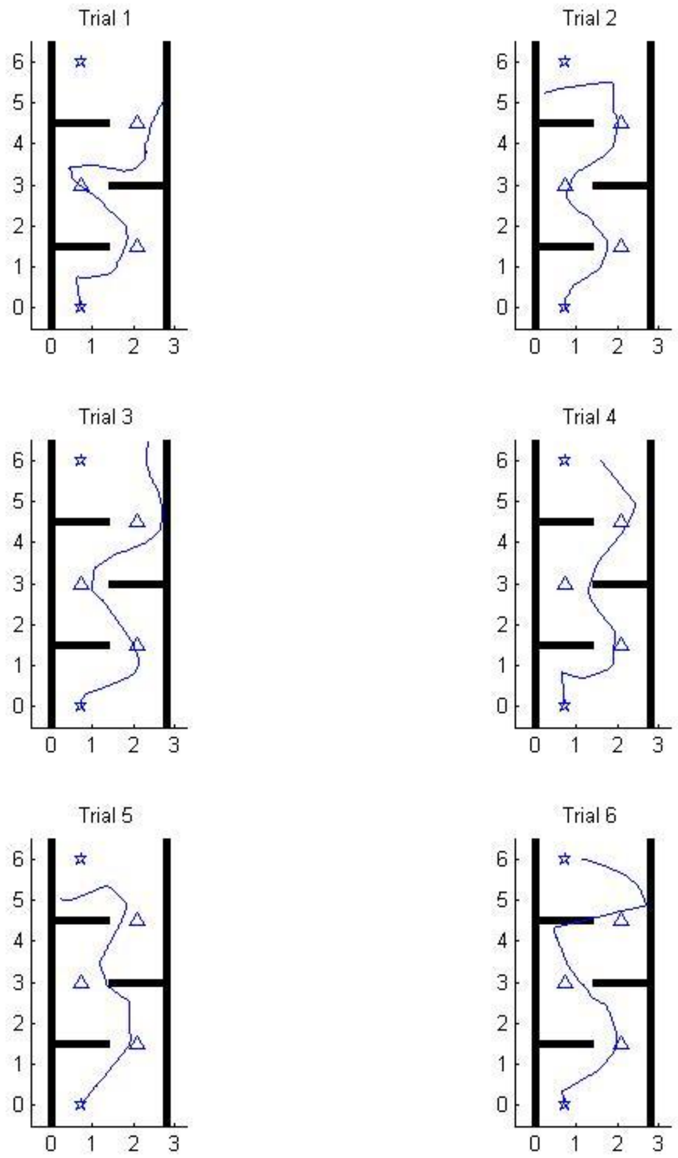


Figure 14 Plots of paths taken by Subject 4 for each trial

Subject 4 successfully completed five of the six trials. During Trial 1, the subject collided with the wall just after passing the third barrier and did not make any further attempt to reach the final goal. The other trials were completed successfully, however. During Trial 5, the subject collided with the third barrier, but was able to navigate around it. During Trial 6, the subject collided with the third barrier and it had to be moved out of the path of the robot. The subject was able to navigate past the third barrier in the last five trials. The deviation from the final intended goal for each trial is shown below.

Table 5 Deviation from final intended goal for each trial completed by Subject 4

Trial number	Deviation from goal (feet)
1	7.378609
2	2.92815
3	5.574475
4	2.867126
5	3.565617
6	1.394357

The time data for each trial completed by Subject 4 is found below.

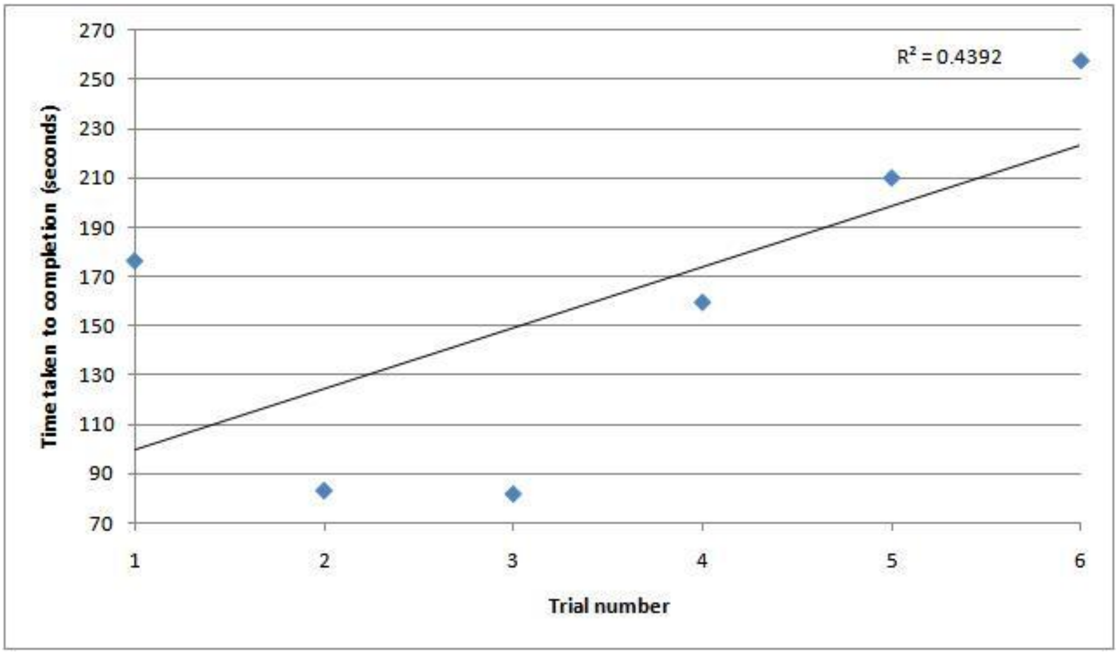


Figure 15 Time taken for each trial versus trial number for Subject 4. Line of best fit shown with correlation coefficient of 0.4392.

The times to completion for Subject 4 range from 82sec to 257sec. Contrary to the expected trend, the data for Subject 4 show an increasing total time for increasing trial number with a fair linear correlation coefficient of 0.4392. It is useful, however, to investigate the data more deeply. After the first initial trial, Subject 4 was quickly able to decrease her time to completion by almost a full minute, from 177sec for Trial 1 to 83sec and 82sec for Trials 2 and 3, respectively. On the second day of testing, Subject 4 showed little retention of driving skill, and the time to completion for Trial 4 was comparable to that of Trial 1. The time for Trial 5 was even slower than the time for Trial 4. On the third day of testing, it appears that Subject 4 exhibited very little retention and completed Trial 6 in the slowest time of all the trials. It is worth noting, however, that Subject 4 exhibited less enthusiasm and less cooperation over successive days of testing, especially on the final day. This certainly had an influence on the time to completion for each trial and can explain, at least in part, the increase in trial time from day to day.

5.1.5 Results from Subject 5

Subject 5 was a thirty-four month-old female. The path for each trial was logged by the onboard computer. The plots for Trial 1, Trial 3, Trial 4, and Trial 6 of the trials were mirrored about the vertical axis for easier comparison. Trials 1, 2, and 3 were completed on the same day. Trials 4 and 5 were completed seven days later. Trial 6 was completed another nine days after that.

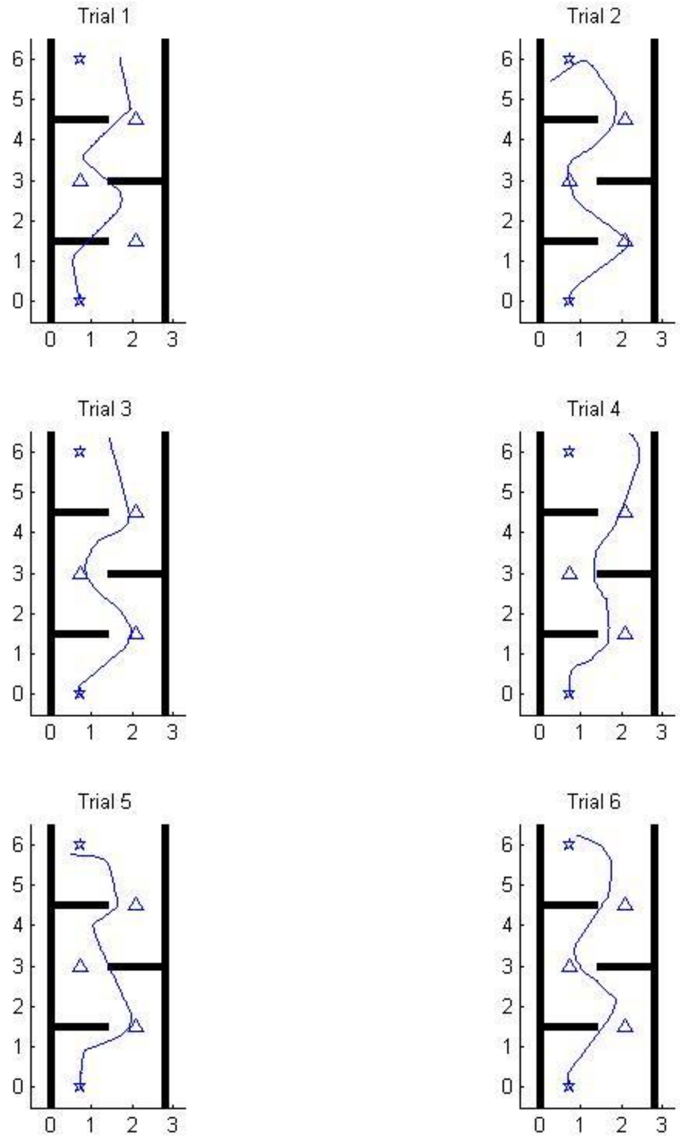


Figure 16 Plots of paths taken by Subject 5 for each trial

Subject 5 successfully completed six trials. During Trial 1, the subject collided with the first barrier and it had to be moved out of the path of the robot. During Trial 5, the subject collided with the second barrier, but was able to successfully navigate around it. The subject was able to navigate past the third barrier in all six trials. The deviation from the final intended goal for each trial is shown below.

Table 6 Deviation from final intended goal for each trial completed by Subject 5

Trial number	Deviation from goal (feet)
1	3.245407
2	2.244751
3	2.600066
4	5.104331
5	1.060696
6	0.991142

The time data for each trial completed by Subject 5 is found below.

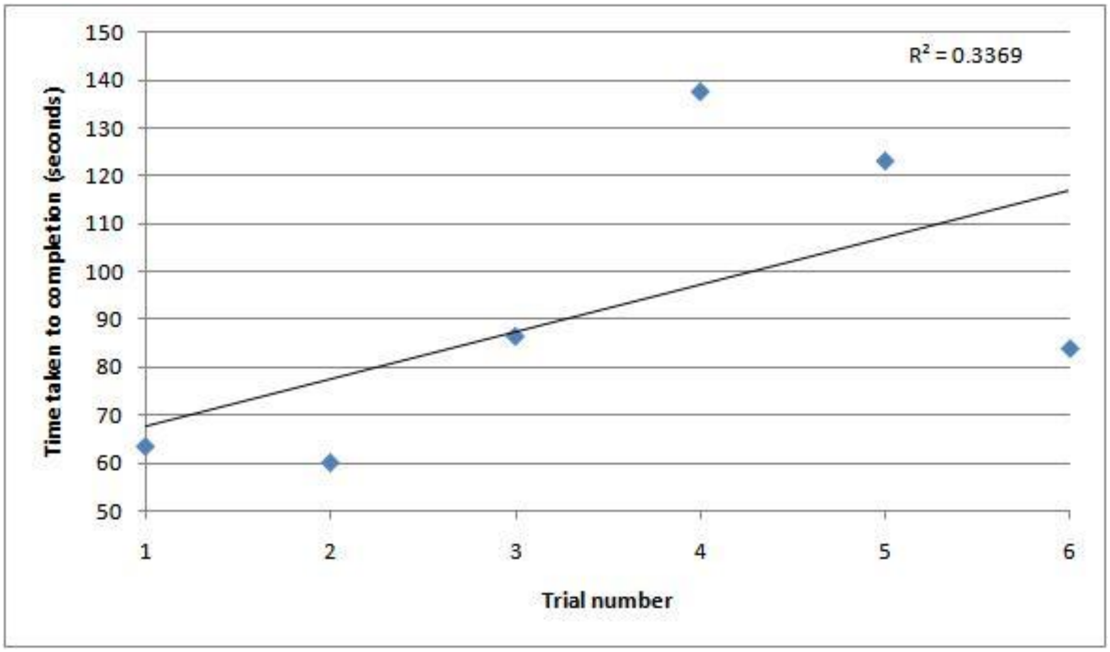


Figure 17 **Time taken for each trial versus trial number for Subject 5. Line of best fit shown with correlation coefficient of 0.3369.**

The times to completion for Subject 5 range from 60sec to 137sec. Contrary to the expected trend, the data for Subject 5 show an increasing total time for increasing trial number with a weakly linear correlation coefficient of 0.3369. Although this does not support the proposed hypothesis, there is useful discussion in this data set. After the first day of testing and the first three trials, Subject 5 showed little retention of driving ability, and the time to completion from the first to second day increased by approximately a minute. Although the subject completed the two quickest trials on the first day of testing, the second and third days of testing show an expected trend, as shown below.

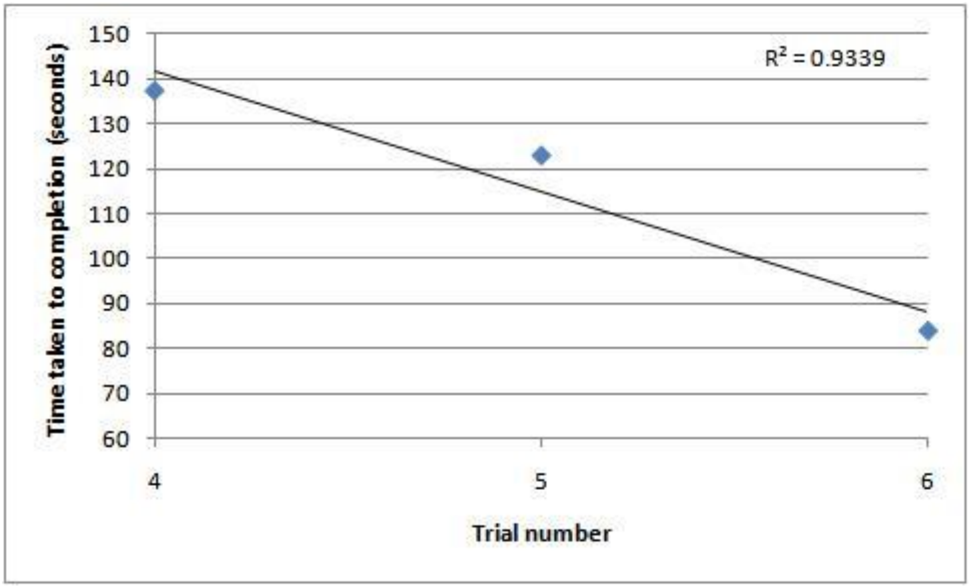
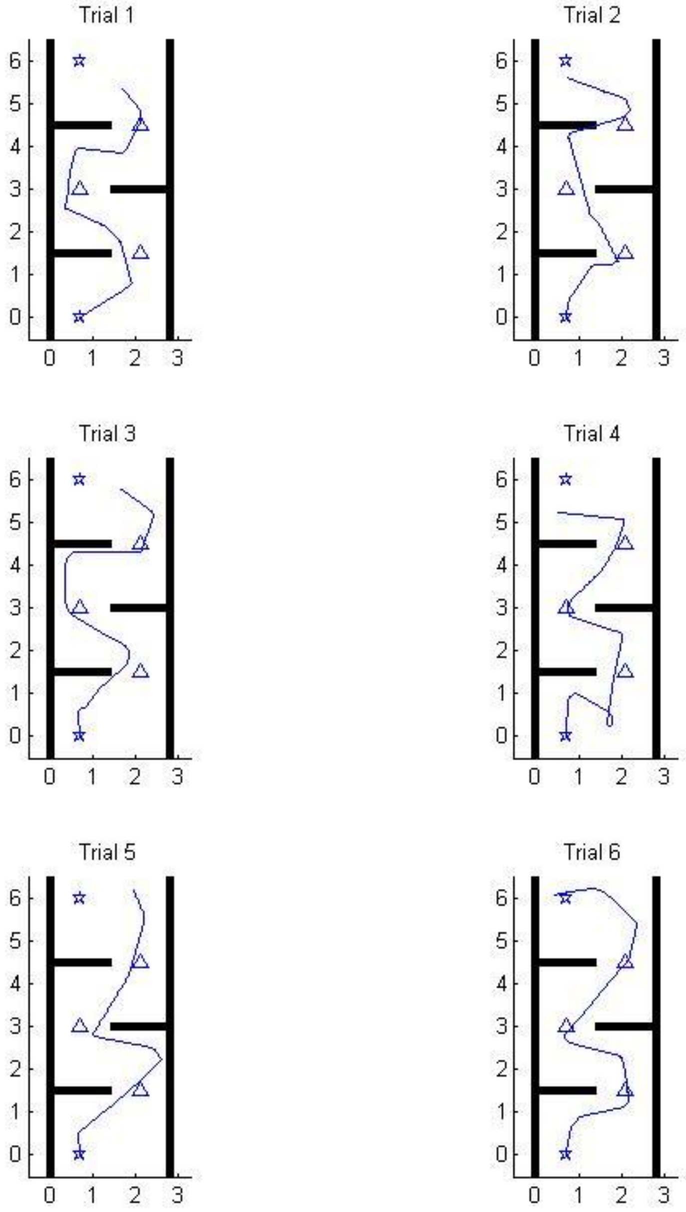


Figure 18 Time taken for each trial versus trial number for the second and third day of testing of Subject 5. Line of best fit shown with correlation coefficient of 0.9339.

For the second and third day of testing, Subject 5 exhibited an expected trend and decrease in time to completion with each trial with a strong linear correlation coefficient of 0.9339. Although this cannot fully support the predicted hypothesis because of the limited number of data points, it suggests that after the first day of testing, Subject 5 began to show improved skill and retention with each trial completed. Additional tests and trials could further support this trend and the hypothesis.

5.2 Atypically-Developing Subjects

Subject 6 is a forty-nine month-old male with spastic cerebral palsy. Because the research is ultimately focused on developing devices to assist atypically-developing children, more attention was given to Subject 6. Subject 6 was seen for ten total trials. The path for each trial was logged by the onboard computer. The plots for Trial 1, Trial 3, Trial 5, Trial 7, and Trial 9 were mirrored about the vertical axis for easier comparison. Trials 1, 2, 3, 4, 5, and 6 were completed on the same day. Trials 7, 8, 9, and 10 were completed two days later.



Trial 1

Trial 2

Trial 3

Trial 4

Trial 5

Trial 6

Figure 19 Plots of paths taken by Subject 6 for Trial 1 through Trial 6

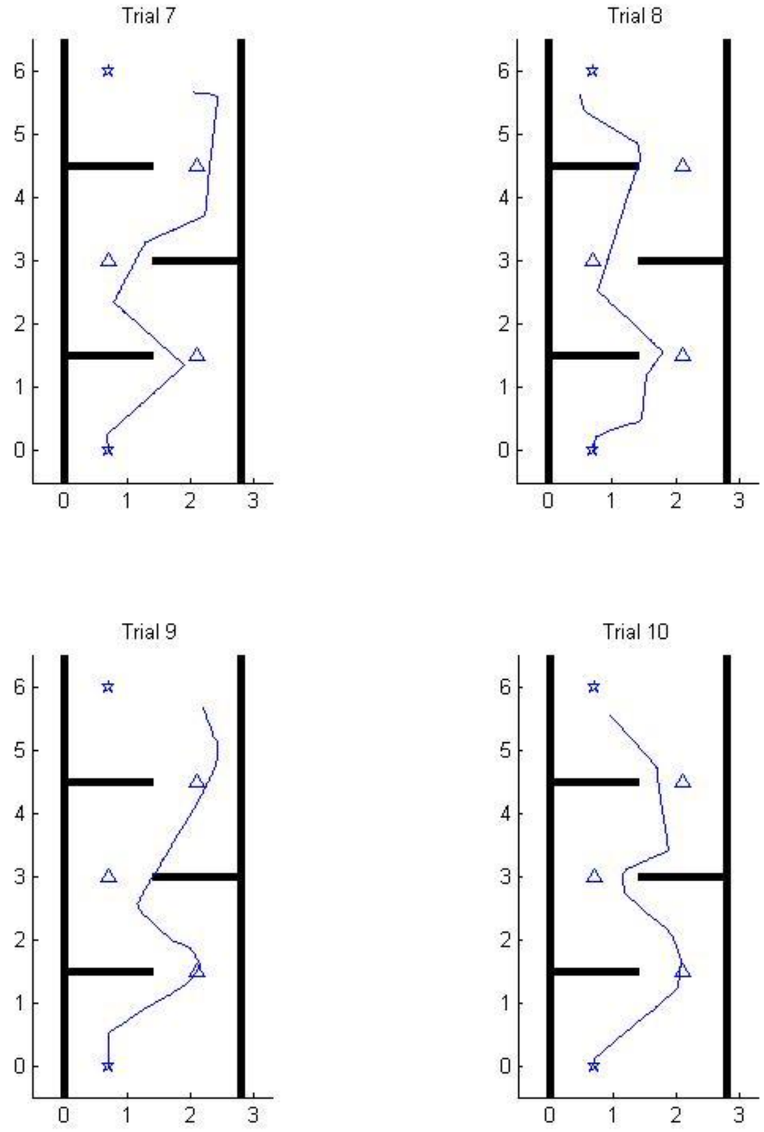


Figure 20 Plots of paths taken by Subject 6 for Trial 7 through Trial 10.

Subject 6 successfully completed ten trials. During Trial 2, the subject collided with the third barrier and it had to be moved out of the path of the robot. During Trial 8, the subject collided with the edge of the third barrier, but was able to navigate around it. During Trial 9, the subject collided with the edge of the second barrier, but was able to successfully navigate around it. The subject was able to reach near the final intended goal in each trial. The deviation from the final intended goal for each trial is shown below.

Table 7 Deviation from final intended goal for each trial completed by Subject 6

Trial number	Deviation from goal (feet)
1	3.956037
2	1.360892
3	3.201772
4	2.632218
5	4.143373
6	0.898622
7	4.547244
8	1.435696
9	5.034777
10	1.779528

The time data for each trial completed by Subject 6 is found below.

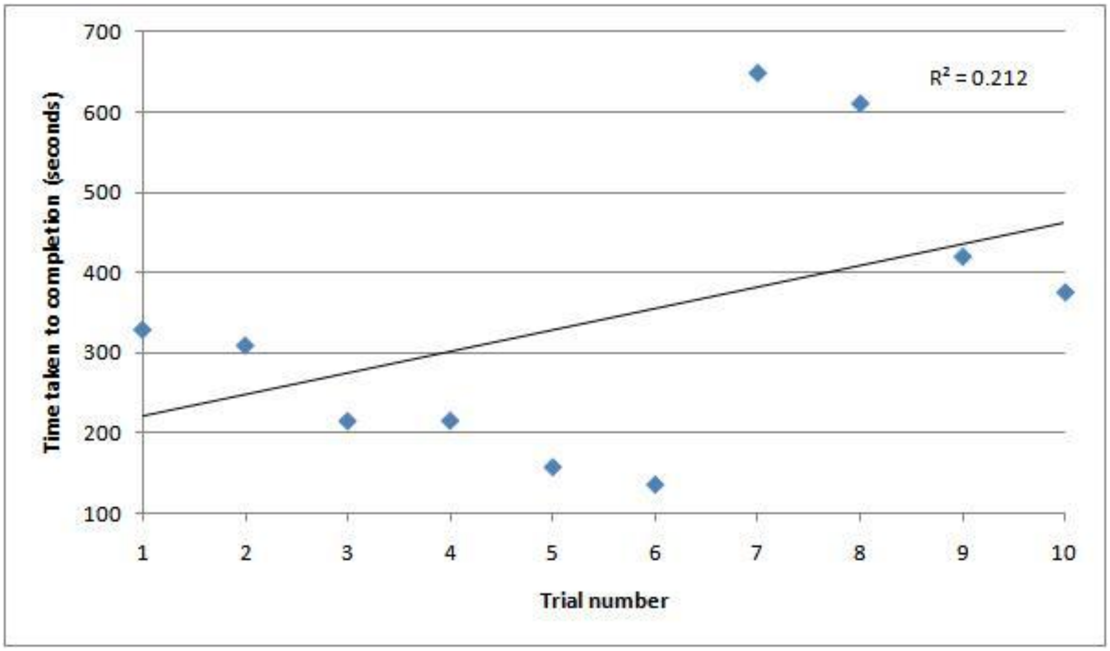


Figure 21 **Time taken for each trial versus trial number for Subject 6. Line of best fit shown with correlation coefficient of 0.212.**

The times to completion for Subject 6 ranged from 136sec to 648sec. This is the largest range exhibited by any of the six subjects. This is as expected, considering the atypical development of Subject 6. Interestingly, the quickest time to completion for Subject 6 was comparable to some of the trial times posted by the typically-developing subjects. This suggests that Subject 6 is not necessarily as hindered in driving the mobile-assistive device as one might initially believe.

The relationship between time to completion and number of trials completed exhibited by Subject 6 seems contrary to the hypothesis. The data exhibit a weak linear relationship with a correlation coefficient of 0.212 and a positive slope, indicating an increase in time needed as the number of trials increases. It is beneficial, however, especially with an atypically-developing subject, to examine the results from each day of testing separately. Subject 6 completed six trials on the first day of testing. The results of time to completion versus trial number from the first six trials are shown below.

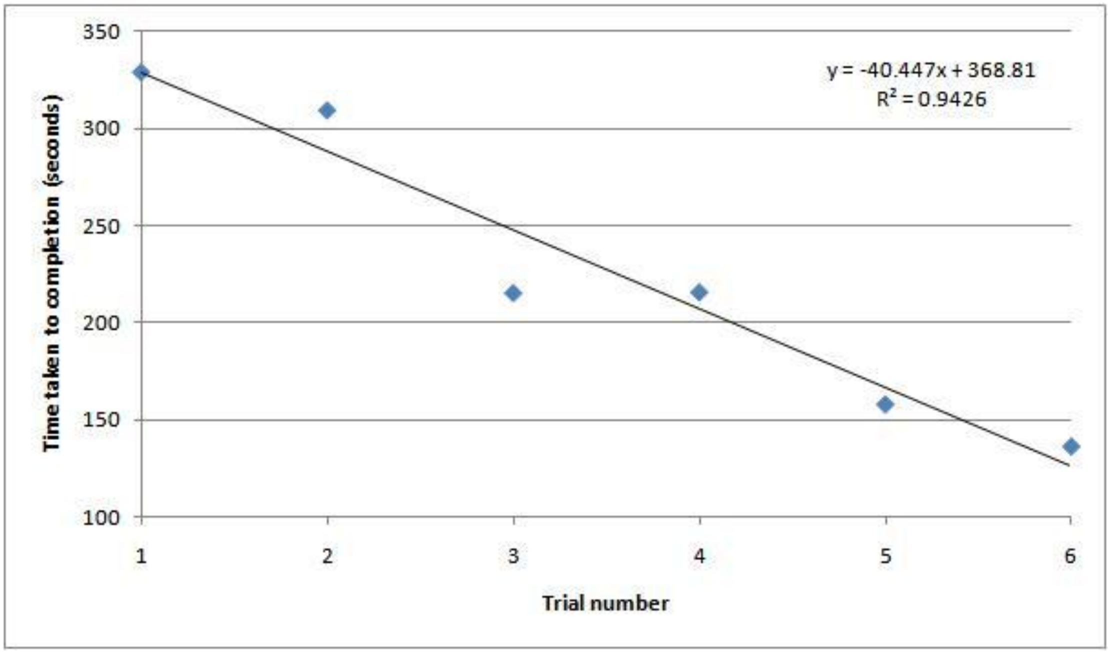


Figure 22 **Time taken for each trial versus trial number for the first day of testing for Subject 6. Line of best fit shown with correlation coefficient of 0.9426.**

The times to completion for Subject 6 on the first day of testing ranged from 136sec to 329sec. The results from the first day of testing exhibit a strong linear relationship with a correlation coefficient of 0.9426. This suggests that as Subject 6 completed more trials on the first day of testing, he became more competent at controlling the robot and also was able to move his legs in a way more conducive to controlling the robot.

Similarly, the second day of testing showed promising results. The results of time to completion versus trial number from the last four trials are shown below.

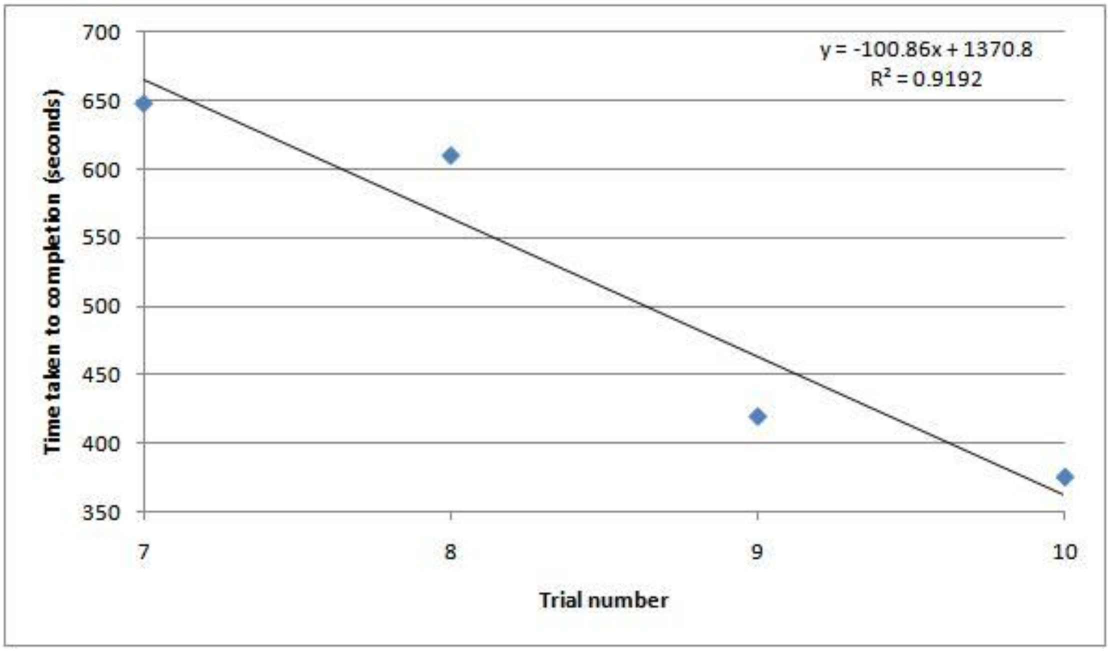


Figure 23 **Time taken for each trial versus trial number for the second day of testing for Subject 6. Line of best fit shown with correlation coefficient of 0.9192.**

The times to completion for Subject 6 on the second day of testing ranged from 375sec to 648sec. The results from the second day of testing exhibit a strong linear relationship with a correlation coefficient of 0.9192. As in the first day of testing, Subject 6 showed an improvement in driving skill and in time to completion through each of the four trials on the second day.

All four trial times from the second day of testing are slower than the six trials from the first day of testing. This appears to indicate a lack of retention of driving ability between the two days of testing. This is not necessarily the case, however. Factors such as fatigue, muscle tension, and muscle pain may have had an effect on the subject's ability to move his legs and his range of motion on the second day of testing, resulting in the slower times. Consideration of these factors can explain in part the increase in time to completion from the first to the second day and weaken an argument supporting a lack of retention of driving ability by Subject 6. Additionally, the trends exhibited on the two days of testing support the subject's ability to retain driving ability between the two days. The slope of the trendline steepened from -40.447 to -100.86 from the first day to the second day, respectively. This increase, and more than doubling, in magnitude of slope of the trendline suggests that Subject 6 became more adept at driving more quickly on the second day of testing. This suggests that the subject did in fact retain and even improved driving abilities from the first day of testing to the second day.

Chapter 6

CONCLUSION AND PATH FORWARD

The main objective of this research was to develop a useful pediatric, bio-driven, mobile-assistive device. All five typically-developing subjects and the one atypically-developing subject were able to purposefully drive the device and successfully navigate through the maze for a number of trials. This suggests that the device is relatively intuitive for the children to drive. Each subject was able to easily activate and drive the robot and coordinate both leg movement and arm movement without extensive training. The largest deviation from the intended goal from all thirty-nine successful trials was 5.87ft, exhibited by Subject 3 in Trial 1. The smallest deviation was 0.56ft, exhibited by Subject 2 in Trial 1. The average deviation over all thirty-nine successful trials was 2.94ft. It should be noted that this value could have been affected by the initial orientation of the robot. The position recorded by the robot is based on a reference set at the initial position of the trial. If the robot’s axle is not situated exactly orthogonal to the plane of the walls of the maze, the entire position log will be rotated by the initial degree offset. This slight rotation is most often not enough to affect the plots in terms of collision with barriers, but is enough to provide a recognizable deviation from the intended goal. Because of this, it is more useful to compare each subject’s average deviation from the goal to the total average deviation from the goal in order to compare each subject’s final accuracy to that of the collective group. No subject exhibited an average deviation more than 0.56ft away from the overall average deviation. This can be considered a success for each subject in terms of purposeful driving.

Over the course of the trials, it was necessary for the researchers to move a barrier out of the path of the robot once for each subject. For five of the subjects, the barrier was removed during one of the subject's first three trials. For Subject 4, this collision occurred on the last trial. As mentioned above, the results from the last few trials of Subject 4 may have been affected and skewed by her decreasing enthusiasm over the course of the experiment. These data suggest that each subject was able to improve driving coordination and ability over the course of his or her six trials. With only six trials for each of five subjects, it is difficult to make conclusive statements regarding the improved driving skills of the subjects over time, but this does suggest some evidence of improvement. It would be reasonable to expect similar results from a larger sample size with more trials.

It was hypothesized that the time required by each subject to complete the maze would decrease approximately linearly as the subject completed more trials. Of the five typically-developing subjects, only two of the subjects showed a general decrease in time required for completion, and only one with any arguably linear relationship. The other three subjects contrarily showed a general increase in time required, and none with any strong linear relationship. Although contrary to what was expected, these results are not too surprising considering the small number of trials, the age group, and the lack of any formalized training. One trend that did seem to arise, however, was the relationship between the number of trials completed per day and the time required for each trial. Of the four subjects that were able to complete three trials in one test day, two of them showed a strong, decreasing linear relationship between time required and number of trials completed. Additionally, on testing days with multiple trials, each subject generally exhibited quicker completion times for the latter trials than those for the former, even if the relationship was not necessarily linear. Subject 1 completed multiple trials on three different days (Trials 1-2 on the first day, Trials 3-4 on the second day, Trials 5-6 on the third). He exhibited a faster time for the second daily trial on two of the three testing days. Subject 2 completed multiple trials on two different days (Trials 1-3 on the first day, Trials 4-6 on the second day). He exhibited successive faster times on one of the two testing days. Subject 3 completed multiple trials on two different days (Trials 1-3 on the first day, Trials 4-5 on the second day). She exhibited a faster time for the second daily trial on the second of the two testing days. Subject 4 completed multiple trials on two different days (Trials 1-3 on the first day, Trials 4-5 on the second day). She exhibited successive faster times on one of the two testing days. For this subject, the data from the second day of testing may have been skewed due to her waning cooperation and enthusiasm for the experimental procedure. Subject 5 completed multiple trials on two different days (Trials 1-3 on the first day, Trials 4-5 on the second day). She exhibited a faster time for the second daily trial on the second of the two testing days. Although it cannot be argued that the subjects were able to exhibit an overall linear decrease in the time needed to complete the maze as they completed more trials, these data support that the children were able to purposefully control and drive the robot and suggest that the subjects were able to improve their driving abilities and speed over the course of the day as they completed more trials. Again, it is difficult to make any strong conclusions, given the small sample size, but it would be reasonable to expect similar results from a larger sample size.

In terms of improving driving coordination and skill over time, the atypically-developing subject, Subject 6, showed results similar to the typically developing subjects. A barrier had to be moved out of the path of the robot only during the subject's second trial, suggesting that his driving coordination improved over time.

Subject 6 did not show an overall decrease in time required for maze completion, contrary to what was initially expected. He did, however, exhibit strong decreasing linear relationships between time required and number of trials completed for each separate day of testing. Of the six trials completed on the first day of testing, only once was Subject 6 unable to complete the maze in a faster time compared to the previous trial. Even in this instance, his time for Trial 4 increased only by less than one second over his time for Trial 3. On his second day of testing, Subject 6 was able to post quicker times for each successive trial over the course of four trials. This is a strong indication of the subject's capability of improving driving ability and time over the course of the day. It is difficult to expand and apply the results of this one subject to a general atypically-developing population, but it does show promise for the concept and the design and encourages further future testing.

The promising results of this experimentation with the initial device encourage further developing and testing. It is anticipated that a larger sample size will more strongly support the trends and results suggested by the six subjects used in this project. Additionally, a more controlled experimental environment, one free of distractions from other children, may provide a setting more conducive to stronger results.

Before much more testing with atypically-developing subjects commences, some redesign considerations should be made. The overall design can be redesigned to reduce its size. Additionally, a more powerful camera with a faster frame rate could improve the resolution and accuracy of the marker velocity approximations. With the current control mechanism, there is a high possible tendency for undesired robotic motion. The child currently is not able to move his or her feet without causing robotic motion. One possible solution to this problem is to have the child use the joystick to indicate the desired direction concurrently with moving his or her feet. This way, if the joystick is not enabled, the child is free to move his or her feet without causing the robot to move. A problem with this, however, is training the child to coordinate joystick movement with foot movement. The learning curve for such a design would be much higher and it is expected that a child would take much longer to master such a device.

In the future, it may be beneficial to remove the joystick entirely from the device. Instead of using a joystick, a child could drive by turning or leaning his or her torso in an indicated direction. Such a control mechanism would further encourage physical development for the children.

For atypically-developing children with spastic cerebral palsy, such as Subject 6, a common motor skill problem is “scissoring”, where one leg crosses over the other during hip flexion. In an attempt to help alleviate and correct this problem, a dividing bar can be added to the robot, separating the left leg from the right leg to prevent any crossover from occurring. For additional atypically-developing subjects, the marker threshold velocities and scaling factors can be individually adjusted in order to match the robotic speeds to the subjects’ gross motor abilities.

Additionally, in order to test the device’s effect on a child’s gross motor skill development, testing will have to be combined long-term with a subject’s progress in a motor skill test, such as the Peabody Developmental Motor Scale. For example, a child’s progress in the Peabody Scale over a six-month period while also using the robot can be compared to the months preceding and following the driving period to test for any change in rate of progress. For short term effects, it would be beneficial to measure a child’s heart rate or breathing rate before and during testing to test whether the device is providing adequate exercise for the child. In conjunction with such measures, any relationship between driving ability, driving time, and gross motor skill function will be able to be investigated.

The initial experimental trials with this robotic design can generally be considered a success. As a result, further development of robot design and testing protocol is recommended to better examine the trends suggested by this research and to investigate new, anticipated trends. This research shows great promise to the eventual development of a fully-functional pediatric, bio-driven, mobile-assistive device.

REFERENCES

1 Bertenthal, B.; Campos, J.; Kermoian, R. “An Epigenetic Perspective on the Development of Self-Produced Locomotion and Its Consequences.” *Current Directions in Psychological Science* 3.5 (1994): 140-145.

2 Caplan, T and Caplan F. *The Early Childhood Years*. New York: Perigree Books, 1983.

3 Bushnell, E. and Boudreau, J.P. “Motor Development and the Mind: The Potential Role of Motor Abilities as a Determinant of Aspects of Perceptual Development.” *Child Development* 64.4 (1993): 1005-1021.

4 Kermoian, R. and Campos, J. “Locomotor Experience: A Facilitator of Spatial Cognitive Development.” *Child Development* 59.4 (1988): 908-917

5 Herbert, J.; Gross, J.; Hayne, H. “Crawling is associated with more flexible memory retrieval by 9-month-old infants.” *Developmental Science* 10.2 (2007): 183-189.

6 Campos, J.; Anderson, D.; Barbu-Roth, M.; et al. “Travel Broadens the Mind.” *Infancy* 1.2 (2000): 149-219.

7 Campos, J.; Kermoian, R.; Zumbahlen, M. “Socioemotional Transformations in the Family System Following Infant Crawling Onset.” In Eisenberg, N. and Fabes, R. *Emotion and its Regulation in Early Development* San Francisco: Jossey-Bass, 1992.

8 Campos, J. and Stenberg, C. “Perception, Appraisal, and Emotion: The Onset of Social Referencing.” In Lamb, M and Sherrod, L. *Infant Social Cognition: Empirical and Theoretical Considerations*. Hillsdale, NJ: Lawrence Erlbaum Associates, 1981.

9 Telzrow, R. “Delays and spurts in spatial-cognitive development of the locomotor handicapped infant.” *Annual Meeting of the International Conference on Infant Studies* (1990).

10 Tefft, D.; Guerette, P.; Furumasu, J. “Cognitive Predictors of Young Children’s Readiness for Powered Mobility.” *Developmental Medicine and Child Neurology* 41 (1999): 665–670.

11 Butler, C.; Okamoto, G.; McKay, T. “Motorized Wheelchair Driving by Disabled Children.” *Archives of Physical Medicine and Rehabilitation* 65.2 (1984) 95-97.

12 Jones, M.; McEwen, I.; Hansen, L. “Use of Power Mobility for a Young Child with Spinal Muscular Atrophy.” *Physical Therapy* 83 (2003): 253–262.

13 Galloway, J.; Ryu, J.; Agrawal, S. “Babies Driving Robots; Independent Mobility in Very Young Infants.” *Intelligent Service Robotics* 1 (2008): 123-134.

14 Lynch, A.; Ryu, J.; Agrawal, S.; Galloway, J. “Power Mobility Training for a 7-month-old Infant with Spina Bifida.” *Pediatric Physical Therapy* 21.4 (2009): 362-368.

15 Ragonesi, C.; Chen, X.; Agrawal S.; Galloway, J. “Power Mobility and Socialization in Preschool: A Case Report on a Child with Cerebral Palsy.” *Pediatric Physical Therapy* (in press)

16 Fattouh, A.; Sahnoun, M.; Bourhis,G. “Force Feedback Joystick Control of a Powered Wheelchair: Preliminary Study.” *IEEE International Conference on Systems, Man and Cybernetics* (2004) 2640-2645.

17 Chen, X.; Agrawal, S.; Galloway, J. “Training Special Needs Infants to Drive Mobile Robots Using Force-Feedback Joystick.” *IEEE International Conference on Robotics and Automation* (2010).

18 Snyder, R.; Spencer, M.; Owings, C.; Schneider, L. “Physical Characteristics of Children as Related to Death and Injury for Consumer Product Safety Design.” Highway Safety Research Institute, University of Michigan. Report UM-HSRI-BI-75-5, Final Report Contract FDA-72-70, May 1975.