The Validation of a Perspective-View

Micro-Computer Based Wheelchair Simulator

by

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(ABSTRACT)

Two perspective-view electric wheelchair simulators were developed to enable therapists to prescribe electric wheelchair control interfaces better. The simulators may also be used to train clients to use control interfaces. One simulator presented the user with the visual perspective of sitting in a wheelchair. The other gave the visual perspective of being behind the wheelchair. The simulators were developed on a micro-computer to reduce their cost and promote more wide spread use in the rehabilitation fields.

This study was to validate the wheelchair simulators by comparing user performance with the simulators to user performance with an actual wheelchair. Four disabled subjects and four able-bodied subjects navigated the simulators and an actual wheelchair through a similar course consisting of a path the width of the wheelchair. Performance measures relating to safety, such as RMS

deviation from the path, number of crossings of the path boundaries, and maximum deviation per trial were obtained for both the simulations and the actual wheelchair driving task. Analyses of variance of these performance measures indicate that mean user performance with the simulators tended to be similar to mean user performance with the actual wheelchair. Correlational analyses suggest that performance with the simulators is predictive of relative performance with wheelchair in straight sections of the course.

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Introduction

A great number of control interfaces are available for electric wheelchairs. Because the suitability of a control interface is dependent both on the characteristics of the control and the individual, the prescription of an interface to an individual is a non-trivial task. An electric wheelchair simulator could provide the therapist with quantified information about the ability of a disabled person to use a given interface. The performance measures derived from data automatically taken by the simulator, such as RMS deviation from a desired path, could relate to safety of the wheelchair user.

The use of a simulator has many advantages over the use of an actual wheelchair in the testing of a control interface. First of all, the simulator would be less expensive to obtain and operate than an electric wheelchair modified to support a large number of control interfaces or a number of specialized electric wheelchairs. Also, the electric wheelchair controls would require more time to reconfigure or adjust for various levels of gain or acceleration rates. A large amount of time would also be required of a highly trained staff member in order to collect performance data from the operation of an electric wheelchair. A computer based simulator could collect data on performance automatically as the simulator was driven. Finally, the simulator would not require a large amount of room in which to operate, as would an actual wheelchair.

A second major benefit of a wheelchair simulator is that of increased safety. A wheelchair user will not be hurt in a simulated collision. The therapist could safely try a number of control interfaces. The wheelchair user, likewise, would not be as likely to fear a novel interface. Thus, performance with different interfaces might not be greatly affected by apprehension or fear. The high level of safety associated with a simulator could also enable the simulator to be used for training purposes.

Purpose

Two PC-based, perspective-view electric wheelchair simulator prototypes were developed to enable therapists to prescribe electric wheelchair control interfaces better. The simulators may also be useful for training disabled clients to use control interfaces. The simulators were developed for an IBM PC/AT or compatible to minimize cost and promote more wide spread use in the rehabilitation fields.

The purpose of this study was to develop and validate the wheelchair simulators. ANOVA's were performed on performance measures to determine if the null hypothesis (there is no difference between user performance with the electric wheelchair and user performance with the simulator) could be rejected. Rejection of this null hypothesis would suggest a lack of concurrent validity. Additionally, correlation coefficients were calculated between performance on each simulator and the wheelchair. The performance measures examined were RMS deviation from the course, maximum deviation from the course, number of times the center of the wheelchair crosses the center-line, the positions of the wheelchair during forty-five and ninety degree turns, and time taken to complete two laps around the course.

Background and Literature Review

Control Interfaces

There are many types of electric wheelchair control interfaces available. The most common type is the proportional joystick. This joystick is usually controlled with the hand and causes the wheelchair to move with a speed proportional to the displacement of the joystick. If the joystick is moved to the right or left, the wheelchair will turn to the right or left, respectively. The standard joystick will return to the null position when released and the wheelchair will come to a stop. In addition to forward motion, the standard joystick permits motion such as spinning in a tight circle and moving in reverse.

The standard joystick controls the displacement of each rear wheel independently. The joystick alters the conditions of two potentiometers or variable inductors, each of which control a wheel. Potentiometers, although common in older wheelchairs, are being replaced by variable inductors, which provide an electronic signal with higher resolution. The potentiometers or inductors have axes of motion which are mutually perpendicular and diagonal to the orientation of the rear wheels (assuming the joystick box is in line with the rear wheels). Displacement of the joystick causes displacement of the potentiometers or inductors along their axes. At steady state (i.e. while not accelerating) the angular velocity of each wheel is directly proportional to the displacement of the joystick with respect to the corresponding potentiometer's or inductor's axis. Because the control axes are diagonal with respect to the rear wheels, a forward displacement of the joystick causes a forward displacement along both axes, causing forward motion of the wheelchair. Likewise, when the joystick is displaced behind the null position, there is a negative displacement along both axes and both the rear wheels will move in a reverse direction. If the joystick were moved directly to the right, there would be a positive displacement along the axis corresponding to the left rear wheel and a negative displacement along the axis corresponding to the right rear wheel, and the wheelchair would pivot to the right.

Electronic circuits read the signal from the joysticks and drive the motors. The ways in which the circuits handle the signal may vary from model to model and manufacturer to manufacturer. Most circuits allow the amount of gain present in the control interface to be selectable. Also, there are different ways to compensate for unintentional displacements of the joystick. These unintentional displacements are common and may be the result of spasticity or athetoid cerebral palsy. Many commercially available systems attempt to compensate for the stray motions by incorporating a variable but interdependent acceleration/ deceleration rate. A slow rate of acceleration may be needed to decrease unwanted accelerations, but an equally slow rate of deceleration may result in collisions.

Many physical modifications may be made to the joystick which greatly affect the user's control of the wheelchair. The size and shape of the joystick is often altered. If the wheelchair user does not have the ability to grasp a small knob, a larger knob may be used. Also, the knobs are sometimes extended so that a disabled person would have an easier time grasping them. If the disabled person lacks the ability to grasp the handle, yet still has some motor function in the arm and hand, the joystick may be modified to include hand supports. For instance, a T-shaped hand tiller, which allows a person to make a turn using supination and pronation motions, is often useful to persons with limited lateral hand/arm movements (Hedman and Kozole, 1986). Other modifications are often required.

In addition to the actual dimensions of the joystick, placement of the joystick is often critical to the optimization of performance. The joystick is sometimes placed in nonstandard positions and orientations to compensate for a limited range of motion or limited strength.

The standard joystick is also often modified to be manipulated by parts of the body other than the hands. Some high level quadriplegics manipulate a joystick through the use of a mouthstick. One end of the mouthstick is designed to be held in the mouth. The other end of the mouthstick has a hook on the end which is designed to fit into a mating hook on the tip of a joystick. The user is thus able to push, pull, and otherwise manipulate the joystick. Other severely disabled individuals manipulate a joystick with their chins or cheeks. In these cases, the joystick is attached to a pad which is within reach of chin or cheek. The pad is manipulated by friction as the user moves the head or chin. Other mechanisms have been designed which allow a user to manipulate a joystick with a linkage which is controlled by head and neck movements. When a user tilts his head side to side, the motion is transferred to a joystick by way of a mechanical linkage. Still other joystick modifications connect the joystick to an arm tray, which is free to translate in a planar motion. The user can manipulate the joystick with gross arm motions as the arm rests on the tray. Some joysticks are even designed to be manipulated by a foot. These joysticks are most often used by individuals with severe deformities.

An experimental interface has been developed which senses the position of the head through Polaroid Ultra Sonic Sensor technology (Jaffe, 1986). With this device, the head itself serves as a joystick without the use of any mechanical linkages.

The type of control input discussed thus far is proportional. Discrete control input is also used extensively to control wheelchairs. The discrete input is most often called switched input. It is either on or off. Switched input signals are usually fed to a special circuit which controls the acceleration and deceleration rate of the wheelchair. The circuit also may allow for latched versus direct control of motion. If latched control is selected, an activation of the switch sets the wheelchair in a motion which is not altered until the user counters the original control input with a second control input. For instance, if a forward motion is selected, then forward motion of the wheelchair is sustained without further input until the user counters the motion with another input. A reverse motion would have to be selected to bring the wheelchair to a stop. Direct control is more similar to proportional input. A control input must be sustained for the desired motion to be sustained.

Switched input is obtained in a number of ways. One common switching device is a joystick. The four switches control a forward and reverse mode for each wheel. When the joystick is displaced, one or two of four switches are closed and the motors are activated. Switched input can also be obtained through the use of buttons. The buttons are usually large and easy to activate. Four buttons which likewise control forward and reverse for each wheel are placed within reach of a severely disabled wheelchair user, usually on a laptray attached to the wheelchair. The user selects one or two buttons to propel the wheelchair. The button functions may also be interrelated so that only one button need be selected for forward motion.

Various other types of interfaces use some form of switched input. Sip and puff controllers decipher sips and puffs of air from a wheelchair user (Kozole, 1986). The interface requires the user to sip and puff air into a tube near the user's mouth. A common version requires the user to give one hard puff for slow forward motion, two hard puffs for medium forward motion, and three hard puffs for fast forward motion. A soft sip causes the wheelchair to turn left and a soft puff causes the wheelchair to turn right. A hard sip causes the wheelchair to go in reverse or to stop if the wheelchair is in forward motion. Hum control interfaces have been developed which decipher hummed notes into control instructions. One such interface requires the user to hum one of four distinguishable notes for forward, reverse, and right and left turns (Aylor, Johnson, and Swanson, 1981). Speech input has also been used to control an electric wheelchair (Amori, 1992).

Control Suitability

Many of the control interfaces used to control electric wheelchairs have inherent disadvantages. An able bodied user would probably find the use of a sip and puff control or a latched switch control a poor interface for controlling a wheelchair. A severely disabled individual, however, may benefit from an interface which removes the fine control from the user. There is a great degree of variance in the motor output of disabled persons, even persons with similar disabilities. This variance allows some control interfaces to be more suited for certain individuals than others. The type of control interface which is best suited for a given individual depends on many factors. Range of motion and the presence and degree of paralysis, spasticity, and strength influence the suitability of a user interface. The amount and quality of kinesthetic and somatosenory feedback also greatly affect the user's ability to manipulate a control effectively. Cognitive and perceptual ability may also influence a user's performance characteristics differently on various interfaces.

The many factors which influence the amount of control a disabled individual is able to exert on a given interface coupled with the wide range of control interfaces available cause the prescription of an electric wheelchair control interface to be a non-trivial task. The problems which result from a nonoptimal matching of control interface to user capabilities range from lowered mobility and frustration to the risk of personal injury. The optimization of control selection, however, enables the user to interact better with the environment. It also provides the user with more confidence and safety.

It is important that the prescription of the control interface take into account important human factors considerations. The system approach must be used in order to provide the optimal interface. Not only must the capabilities of the control interface be considered, but the capabilities of the user and the characteristics of the operating environment must also be taken into account. If the wheelchair is to be used predominantly indoors, then perhaps it is more important that the control interface allow the user to avoid obstacles and maneuver sharply. If the interface is to be used predominantly outdoors, then the interface must not be sensitive to factors such as the weather or inclines. For example, the weight of an arm may act differently on a control if the wheelchair was going down a steep incline as opposed to rolling on a level surface. Of course, most variables are important whether the wheelchair is to used indoors or outdoors, but the relative importance of different variables may have different weightings.

Prescription Methods

The prescription of control interfaces requires a knowledge of both the individual and the interface. Several attempts have been made to measure the performance of disabled individuals with an isolated interface, that is, an interface not being used to control a device such as a wheelchair. Law (1986) developed an adjustable mounting joystick control box and a connected Visual Corresponding Coordinate Display (VCCD). The VCCD provides the user with feedback from LED bar graphs. The VCCD shows the displacement of the joystick in terms of its component vectors. The ability to manipulate the joystick is reflected by the LED displays. Barker and Cook (1981) emphasize the use of performance variables such as time taken to reach and activate the interface from a resting position, time taken to change an input, and input selection accuracy in determining the suitability of a control interface. Although no methods of evaluation are mentioned, Barnes (1991) suggests looking for control sites on wheelchair candidates which have movements which are reproducible, sustainable, quick, and accurate. These approaches, however, do not consider the use of the control interface from a system perspective. That is, the behavioral characteristics of the device to be controlled may interact with user performance with a given interface in the accomplishment of a task.

The guidelines used to prescribe electric wheelchair controls vary from agency to agency. The Cerebral Palsy Research Foundation in Wichita, Kansas, relies mainly on the personal experience and insight of the staff when prescribing electric wheelchair controls (Susan Scholl, personal communication, January 30, 1989). Whenever possible, a standard proportional joystick is chosen because of its lower cost. If a staff member questions the appropriateness of an interface, the staff member will hold the interface in a desired position while the wheelchair user attempts to manipulate it. No quantified data is obtained on user performance.

Bayer (1986) recommends the use of a crude simulation technique to determine the control interface most suitable for an individual with cerebral palsy. To incorporate this technique, the therapist first subjectively determines that the use of a standard joystick is inappropriate for a disabled client. The therapist is to ignore the availability of input devices and rely on imagination. The client is examined for possible control sites which could supply at least four input signals. The therapist then constructs a mock control interface out of cardboard, tape, foam rubber, etc., and gives the mock-up to the client, who is in a manual wheelchair. The client is asked to pick a destination and manipulate the control so as to drive there. While the client uses the mock-up, the therapist pushes the manual wheelchair as if responding to the control input from the client. The suitability of the control interface is determined by the client's ability to "maneuver" the wheelchair using the control mock-up.

There are several problems associated with the use of the simulation technique discussed above. First of all, the evaluation is purely subjective. The therapist must interpret the manipulation of the mock-up control. In doing so, the therapist is likely to understand what the client is trying to do and may bias the experiment by pushing the client where the client wanted to go. Because the therapist is the one to develop the control interface, the therapist may set out to prove that it works well. Even a totally unbiased therapist would not be able to interpret the control input and respond consistently without error.

Several rehabilitation facilities use wheelchairs which are configured to accept input from several types of controls as a means for testing control interfaces. The University of Tennessee Rehabilitation Engineering Program, for instance, employs an adaptable wheelchair to aid in the evaluation of the total wheelchair configuration (Taylor, 1986). This simulator consists of a Fortress Scientific power base with a contour fitting polystyrene bead filled seat attached to a vacuum pump. Once molded to the desired shape, the contours of the seat can be fixed by removing the air. The wheelchair has an adjustable control mount that allows for several types of controls to be placed in several positions. The client can thus be observed using a variety of controls. Southwick (1986) also describes a similar evaluation method which makes use of a Fortress Scientific wheelchair with exchangeable seats and control interfaces. Hannemann (1988) describes a similar approach in which a power wheelchair has been modified to allow several configurations of switches to be attached.

The Powered Wheelchair Mobility Simulator (PWMS), a powered base on which a manual wheelchair can be mounted, has been designed to assess the ability of young clients to use a powered wheelchair (Hull and Schmeler, 1992; Schmeler, 1992). This device allows clients to be seated in their own manual wheelchairs, yet drive the base as in a powered chair. This base is compatible with a variety of controls and behaves much like a standard powered wheelchair. Although the base is designed to assess the ability of a client to use a wheelchair, it has not yet been formally tested and validated. One possible problem with this device is that it has a wheel base which is significantly longer than a standard powered wheelchair, and thus behaves differently in turns.

The use of an actual wheelchair to test the usefulness of control interfaces is a big improvement over the use of crude simulation techniques or the examination of the control interface out of context with the whole wheelchair system. A wheelchair which is modified to accept a number of wheelchair controls has several draw-backs, however. First of all, the wheelchair very likely would be expensive. The wheelchair would require a large open area in which to operate. No research indicated that quantitative data on wheelchair performance with various controls were taken to aid in the prescription process. Perhaps performance measures, such as deviation from a path, are too difficult and time consuming to obtain for a large number of clients. A second disadvantage of the use of an actual wheelchair to test control interface performance is that of reduced safety. The client might be asked to try a control that he or she cannot control or is afraid of. Fear of a novel control may influence user performance, thus biasing the evaluation. Finally, the therapist might be afraid to try an unusual interface because of safety considerations when, in fact, the interface could be appropriate.

Computer Simulations

The use of a computer-based wheelchair simulator to evaluate performance of a client with a control interface might be of great value. This approach has been studied in only a few studies, most of which involved bird's-eye-view simulators. The study of one such simulator, run on a NOVA 2, failed to draw any conclusion about the ability of simulator to assess a person's ability to handle a wheelchair (Pronk, de Klerk, Schouten, Grashuis, Niesing, and Bangma, 1980). The authors concluded that a simulator may have usefulness as one of several aids used in an electric wheelchair evaluation. Another bird's-eye-view simulation has been developed on a Commodore 64 to enable disabled children to practice using a joystick (D. Peterson, personal communication, February 22, 1989). This simulation was never evaluated for fidelity or usefulness, but the creator states that it seems to be useful in teaching children to use a joystick. A third bird's-eye-view simulator has been developed for an Apple IIe as part of a larger study which also included a three dimensional wheelchair simulator (Field, Verburg, and Jarvis, 1987; Jarvis, Lotto, Staub, Young, and Verburg, 1987). This bird's-eye-view simulator was determined to be a reliable predictor of wheelchair performance with able-bodied children (ages four to nine) but not with disabled children. The authors suggested that the able-bodied children were better able to decentrate, that is, understand the object's movement from its point of view. It was also demonstrated that a radio controlled toy jeep could be used to predict wheelchair performance with able-bodied but not disabled children. Performance was measured by two variables: number of paddle reads obtained during the navigation of the course and number of times the wheelchair collided with the side of the course. A paddle read is the polling of the joystick by the computer. Because the number of paddle reads is roughly a linear function of time, the performance measure relating to paddle reads also relates to time.

While a two-dimensional wheelchair simulator was determined to be useful in predicting wheelchair performance for able-bodied children, a perspective-view wheelchair simulator was found to predict wheelchair performance with disabled children (Field et al., 1987; Jarvis et al., 1987; G. Verburg, personal communication, February 23, 1989). The perspective-view simulator was found to be a good predictor of both low speed and high speed wheelchair performance measured in paddle reads taken to complete a course. A paddle read was a reading of the position of a joystick by the computer which occurred at regular time intervals. It was also a good predictor of high speed wheelchair performance measured in number of collisions during navigation of a course. The performance of able-bodied children with the perspective-view simulation was not found to be a significant predictor of their performance with an actual wheelchair. This result may have been due to limitations of the simulation.

The study by Field et al. and Jarvis et al. discussed above has several potential weaknesses. First of all, the performance measures used may not have been good indicators of wheelchair performance. Perhaps a measure of time taken to complete the course could have been substituted for number of paddle reads obtained during the completion of the course. Also, because the wheelchair courses were six feet wide, the number of collisions with the side of the course may not be a sensitive measure. Many performance measures, such as joystick direction changes and length of time in collision, were taken and presumably analyzed, yet the results were neither displayed nor discussed. Results from an analysis of variance indicated that there was a significant difference between performance by able-bodied subjects and disabled subjects, but the difference between performance measures taken from the simulator and actual wheelchair was not addressed. The simulation package itself may have not adequately modelled wheelchair behavior. The simulator could not recover from a collision in the same manner as a normal wheelchair (G. Verburg, personal communication, February 23, 1989). The simulation would require the user to back up instead of bouncing off the side of the course as the control wheelchair did. This behavioral difference could affect the performance measure of number of paddle reads per course navigation because the simulator would take longer to recover from a collision. The relatively slow speed of the Apple IIe used in the simulation may also have affected the usefulness of the simulation. Studies in manual control theory have suggested that if a simulator does not respond to a user's input within thirty milliseconds, the performance of the system is decreased (W. Wierwille, personal communication, April 13, 1989).

Another microcomputer-based wheelchair simulator has recently been developed (Smith, Mathews, Scott-Talpin, and McLaughlin, 1990; McLaughlin, Scott-Talpin, Mathews, and Smith, 1988; Smith, and McLaughlin, 1988). The simulator runs in either a two dimensional or three dimensional mode. It also allows the user to select from one of several simulated environments in which to operate or to design a custom environment. The large amount of detail obtainable in the environments limits the speed of the simulation, however. The maximum speed obtainable in a simple simulated environment is ten screen updates per second. A more detailed environment causes an even slower computer response time. This slow computer response time would probably interfere with user performance on the system. The simulator is to be used for both testing and training of wheelchair users, but has not yet been validated. It is currently being informally reviewed by a number of rehabilitation facilities. Currently, the simulator does not take any performance data. A therapist can, however, observe performance and make subjective ratings. This package runs on an Amiga or IBM PC computer.

Based on the literature, it appears as though there exists a need for a perspective-view computer-based wheelchair simulator to aid in the evaluation of control interfaces for potential powered wheelchair users and to provide some powered wheelchair training. The simulator should be capable of responding to user input within about thirty milliseconds. In order for the simulator to be most useful for the prescription of control interfaces, quantitative data must be taken which relates to wheelchair performance. The performance measures should reflect the amount of safety associated with a control interface for a given individual.

The simulator should also fairly accurately model wheelchair behavior. Finally, the simulator should be validated to demonstrate that performance with it is similar to performance with an actual wheelchair. This study was an attempt to validate such a wheelchair simulator prototype.

Method

Two wheelchair simulators were developed and tested to determine if user performance with a simulator would be similar to user performance with a wheelchair. The simulators and wheelchair were driven around similar courses and positional data were recorded. Performance measures were derived from these data and analyzed through analyses of variance and correlational analyses to determine if the devices yielded results which were significantly different.

Experimental Apparatus

The electric wheelchair simulation programs were written for an IBM PC/AT or compatible. This computer was chosen because of its relatively low price and its common usage at the time the experiment was conducted. The IBM PC/AT was chosen over a MacIntosh after a bench test of the program in an early state of development demonstrated that the program ran faster on an IBM PC/XT than on a MacIntosh SE. The IBM PC/AT also supports many peripheral devices, such as the inexpensive A/D converter board used by the simulation program to monitor the joystick position.

The simulation programs were written in the language C and compiled with the Turbo C compiler. It was run on a 16 MHz Kaypro 286, which is compatible with the IBM PC/AT. The computer had a 10 MHz math-coprocessor to quicken the numerical calculations required in the generation of the path on the screen. The display used was a 12 inch amber monochrome monitor which gave a high resolution display (720 x 348 pixels). A Fresnel lens with a focal length of 12 inches was used to enlarge the image on the screen and give the user a feeling of depth by creating a virtual image of the path several feet behind the actual screen. The position of the potentiometer-based joystick was sensed and converted to a digital signal by an IBM Data Acquisition Board. With the equipment listed above, it was possible for the program to calculate a new wheelchair position and generate the appropriate perspective-view image on the screen over twenty-five times per second. This rate was fast compared to that of other published computer-based wheelchair simulators. The simulator designed for the Amiga has a maximum refresh rate of ten per second (Smith et al., 1988). The refresh rate of the simulator designed for the

Apple IIe was not given (Jarvis et al., 1987), however, the Apple IIe is not a fast computer.

The wheelchair simulations displayed a perspective-view course on the screen. The course was similar in dimension to an actual wheelchair course laid out in tape on the floor in a large room. The dimensions of the courses may be seen in Figure 1. The course was generated so that it appeared to move toward the user as the user propelled the wheelchair forward. Likewise, the path rotated around the user when the user turned. The course contained both ninety and forty-five degree turns which the user was required to navigate.

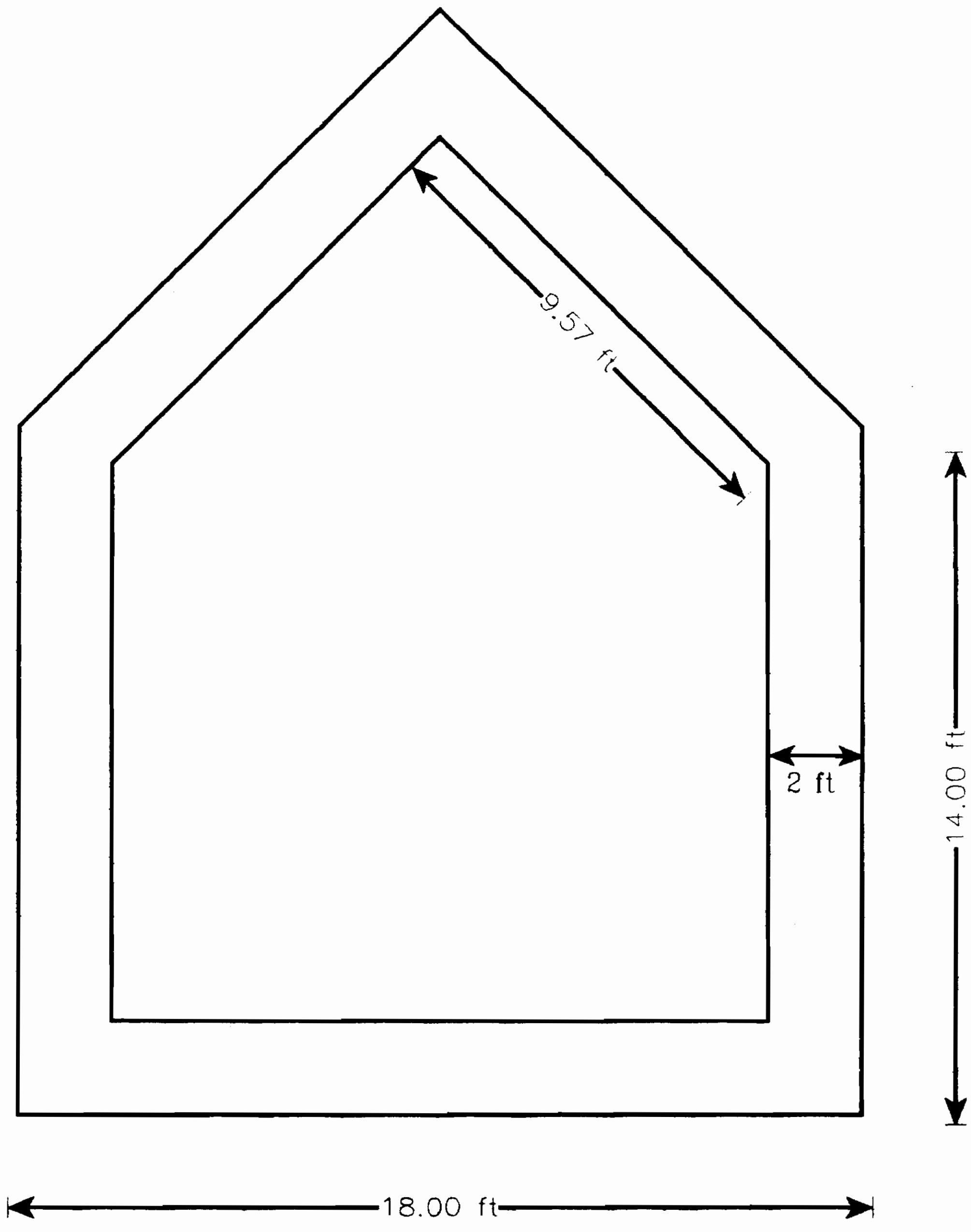


Figure 1. The course followed by the wheelchair and the simulators had the same dimensions.

The two simulators which were developed and tested were identical except for the visual perspective given to the user. As seen in Figure 2, the on simulator gave the user the visual perspective of sitting in the wheelchair. This perspective is often referred to as "inside/out". From this perspective, two round objects, representing knees, appeared at the bottom of the display. The knees aided in the positioning of the wheelchair on straight portions of the course. The portion of the course on which the rear wheels roll is below the user in an actual wheelchair and therefore off the screen in this simulation. This perspective provided a sense of realism when maneuvering down a straight section of path, but may have caused difficulty in maneuvering around a sharp bend. The difficulty came from an inability to see the position of the rear wheels with respect to the path. Most actual wheelchair users are able to move their heads in order to know where they are with respect to an object they are maneuvering around. The use of a microcomputer simulation, however, imposes limits on the amount of realism obtained. The effect of a such a small field of view is similar to allowing a wheelchair user to look only through a small window straight in front of the face. One could expect a performance decrement as a result of this limitation.

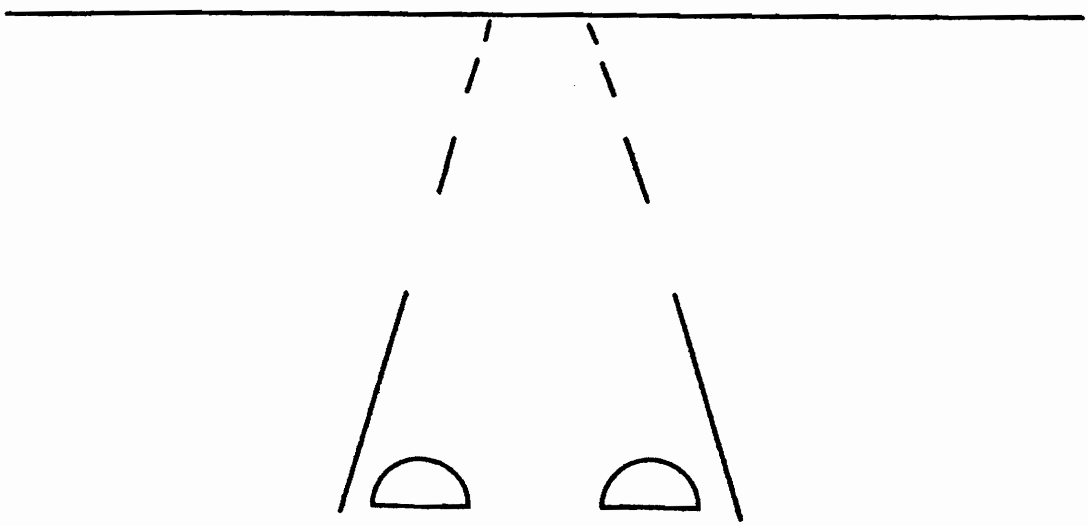


Figure 2. The on simulator gave the visual perspective of sitting on a wheelchair.

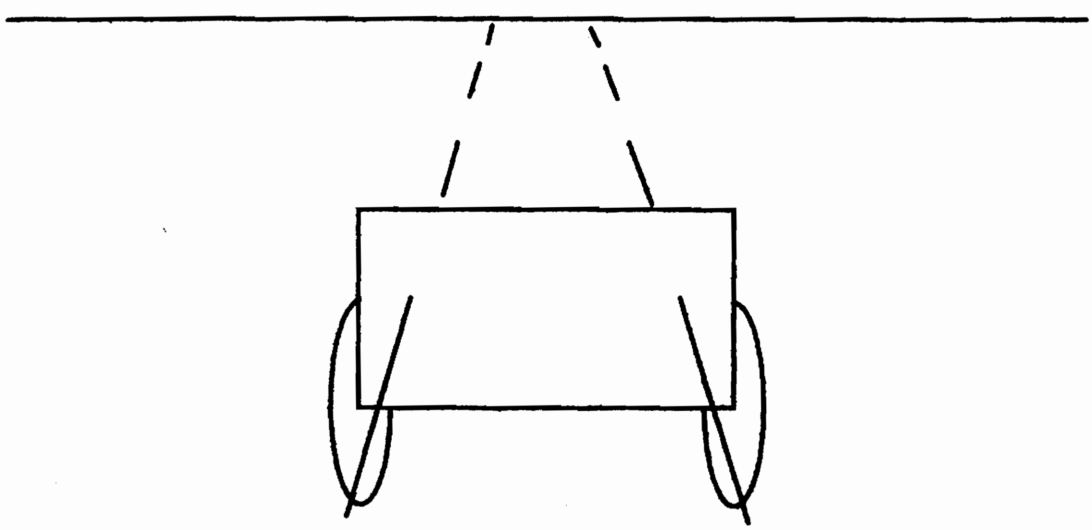


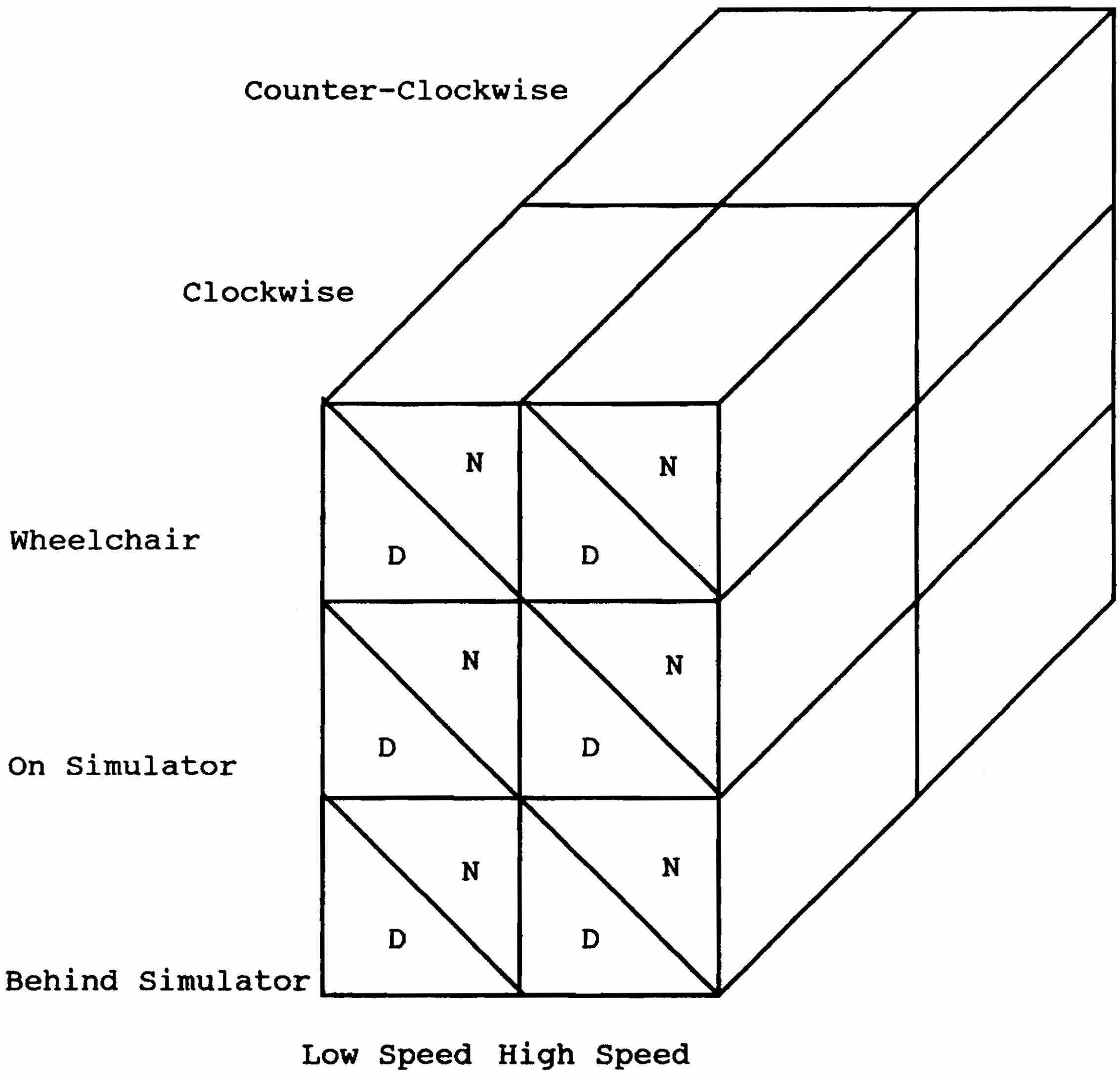
Figure 3. The behind simulator gave the visual perspective of being behind a wheelchair.

The second simulator, the behind simulator, gave the visual perspective from the point of view of two feet behind the wheelchair. This type of simulator is often referred to as "outside/in". The visual perspective of this simulator may be seen in Figure 3. From this point of view, the rear wheels of the wheelchair could be seen. This simulator was developed to determine if performance during the navigation of sharp turns required a visual reference of the rear wheels with respect to the course in order to model performance in an actual wheelchair. The ability to see the rear wheels with respect to the desired path may aid in the ability to keep the wheelchair on the path, both on the simulator and in the actual wheelchair.

The turning and velocity characteristics of the wheelchair simulators were designed to match to those of an Invacare Rolls IV, the actual electric wheelchair used as a control. The values of the variables used to simulate the wheelchair performance characteristics were chosen using subjective means. In a pretrial study, three pre-experimental subjects who were not affiliated with the experiment drove both the on simulator and the wheelchair. As these subjects alternately drove the on simulator and the wheelchair, the values of the variables defining the amount of simulated momentum were adjusted in an iterative manner until the subjects felt that the on simulator behaved similarly to the wheelchair. The response dynamics of the behind simulator were set to match those of the on simulator.

Experimental Design

The experimental design consisted of a 3x2x2x2 mixed-factor design. The design matrix is shown in Figure 4. Across one dimension of the matrix is the device within-subject variable. The driving of an actual wheelchair is the control treatment. The other two devices are the simulation presented from the perspective of sitting on the wheelchair (on simulator) and the simulation presented from the perspective of viewing the wheelchair from two feet behind (behind simulator). The second dimension of the matrix contains wheelchair speed settings, also a within-subject variable. The first speed setting limited the maximum speed to 2.2 miles per hour. The second speed setting limited the maximum speed to 3.3 miles per hour. While current wheelchairs provide greater speeds of five to eight miles per hour, the two levels used in this study were defined by the two levels available with the actual electric wheelchair being used as a control. The final within subject treatment was the direction of travel. When subjects drove clockwise around the course, they made only right hand turns.



Note: D denotes Disabled
N denotes Non-disabled.

Figure 4. The experimental design was a 3x2x2x2 mixed factorial design

Counter-clockwise travel involved left hand turns. The between subject variable, which was along the third dimension of the design, consisted of a disabled group and an able-bodied group of subjects.

The order in which the two simulations and the wheelchair were used, in combination with the two levels of gain, differed for each subject. A partially balanced Latin square design was used to eliminate possible training effects. The Latin square design was not fully balanced because two disabled subjects failed to participate in the study and were not able to be replaced. In order to have an equal number of disabled and non-disabled subjects, the data from the two non-disabled subjects which received the same experimental treatment order as the absent disabled subjects were thrown out.

Dependent Variables

The course consisted of straight sections and sharp ninety and forty-five degree turns. The course was represented by dashed lines in the simulation. It was laid out in tape in a large room for navigation by an actual wheelchair. The position of the simulator or wheelchair relative to the centerline of the course was recorded every six inches.

This position was the deviation of point on the wheelchair mid-way between the two rear wheels from the centerline of the course. From these data, performance measures relating to wheelchair control were calculated. The floor on which the experiment was run was covered with twelve inch square tiles and thus lent itself to an easy discrimination of six inches. A mock trial, in which the author and a colleague drove the wheelchair around the course to be used in the experiment, revealed that the RMS deviations calculated from measurements taken at six inch intervals (2.294 in. and 4.078 in.) were similar to those calculated from measurements taken at three inch intervals (2.304 in. and 4.050 in.). This finding was consistent both when the deviations were large and small. RMS deviations calculated from measurements taken at twelve inch intervals were likewise similar (2.257 in. and 4.183 in.), but some information from sudden swerves was lost.

Separate performance measures were derived for turns and straight sections of the course. The performance measures derived for the turns differed from those derived for the straight sections of the course for several reasons. First, because the turns were sharp and not gradual bends, they could have been navigated in several acceptable manners. For example, in navigating a sharp ninety degree right turn, the wheelchair user may have pivoted the wheelchair by stopping the right wheel and propelling only with the left. Another way in which the wheelchair user might have turned would have been to spin the wheelchair, turning the right wheel backwards and the left wheel forwards. The quality of the turn, therefore, might not be determined best by the path that the wheelchair took, but rather by the position of the center of the wheelchair immediately before a turn. In a straight section of path, however, the quality of control would best be determined from the path that the wheelchair took. Another reason why performance measures relating to turns should be differentiated from performance measures relating to straight sections of the course is that different control interfaces may have different control characteristics for various maneuvers. An individual might find some controls appropriate for straight navigation, but unsatisfactory for navigating a sharp turn. Also, scores such as RMS deviation from a straight path might not be meaningful in describing a sharp turn. Finally, the visual cue limitations of the simulations may have different effects for straight sections of path and sharp turns. That is, the simulated view from the perspective of the wheelchair user, which does not allow the user to see the rear wheels, may work poorly on a sharp turn but satisfactorily otherwise. Conversely, the simulated view from the perspective of two feet behind the wheelchair may yield better results through a turn but work poorly otherwise.

Performance measures for navigating a straight section of the course were derived from data recording the position of the wheelchair with respect to the course, taken every six inches. The first dependent variable was Root Mean Squared (RMS) deviation from the course. A second measure of performance was the maximum deviation from the course. This measure is important because an occasional large deviation may indicate an inability to control the wheelchair safely. An interface which performed satisfactorily most of the time, yet occasionally led to collisions, might not be considered appropriate. A third measure of performance for straight sections of path was the number of times the center of the wheelchair crossed the center line of the path. In order for the movement to be counted as a crossing, a minimum perpendicular displacement of one inch on each side of the center line had to occur. This qualification is intended to limit the effect of small deviations around the center line. The performance measures relating to straight sections of path were calculated from data recorded from straight sections of path at least eighteen inches away from the beginning or end of a turn. The points immediately before and after a turn were discarded so that the effects of turning behavior on these performance measures could be reduced.

A final measure of performance was the time taken to complete two laps around the course. This performance measure encompassed both behavior on turns and straight sections of the course.

In addition to the performance measures taken, subjective evaluations were taken after the use of each simulation. The subjective evaluations were in the form of bipolar rating scales and may be seen in Appendix C. They were used to assess relative difficulty, realism, and usefulness of simulations. The results of these scales may be seen in histogram form in Appendix D. Open ended questions were given after the experimental session to allow the subjects to further express opinions and suggestions. These questions and their results may be seen in Appendix E.

Subjects

Four quadriplegic subjects were recruited from the New River Valley area. Originally, six disabled subjects were scheduled, but two repeatedly failed to show up. The number of subjects used was limited by the small population of quadriplegics in the area. The level of disability varied from subject to subject, but each had some degree of upper limb involvement. The disabled subjects all had wheelchair experience. In addition to the disabled subjects, six able-bodied student subjects were recruited from Virginia Tech. By coincidence, all subjects who participated in this study were males. Although six non-disabled subjects were run, two were discarded so that analyses of variance and Newman-Keuls tests could be performed on an equal number of disabled and non-disabled subjects. The two which were discarded received the same treatment order as the two disabled subjects who failed to participate. None of the non-disabled subjects had any experience with the simulation package or powered mobility devices. All subjects were paid five dollars per hour for their time.

Experimental Procedure

Upon beginning the experiment, the subject was seated in the electric wheelchair supplied by the lab. Disabled subjects were seated on their own cushions, if available. Otherwise, a cushion was made available to each subject.

The subjects were asked to perform twelve tasks. The tasks, which were given in a different order for each subject are listed below.

1. Wheelchair driven clockwise in low speed.
2. Wheelchair driven counter-clockwise in low speed.
3. Wheelchair driven clockwise in high speed.
4. Wheelchair driven counter-clockwise in high speed.
5. On simulator driven clockwise in low speed.
6. On simulator driven counter-clockwise in low speed.
7. On simulator driven clockwise in high speed.
8. On simulator driven counter-clockwise in high speed.
9. Behind simulator driven clockwise in low speed.
10. Behind simulator driven counter-clockwise in low speed.
11. Behind simulator driven clockwise in high speed.
12. Behind simulator driven counter-clockwise in high speed.

Spring-loaded, paint-based crayons were used to record the path taken by each subject as he navigated the course in the wheelchair. A different color was used for each trial. Positional data were collected from the crayon marks after each subject finished the experiment. Simulator data were collected automatically.

The subjects were instructed to follow the path as quickly as possible, while maintaining accuracy, that is, staying close to the center. Because the path was only as wide as the wheelchair, the subjects were told they could expect to deviate from the path, but should keep that deviation to a minimum. After each trial involving the simulator, the subjects were asked to respond to a set of nine bipolar rating scales evaluating their perception of the simulation.

Before beginning any of the tasks, the subjects were required to practice the task for three minutes. Before the subjects were allowed to drive the actual electric wheelchair around the course, they had to demonstrate a level of proficiency by driving the wheelchair through a six foot wide by ten foot long course laid out in the center of the room. The total time that subjects spent during the experiment was no more than two hours.

Data Analysis and Results

Several dependent variables were derived from measurements of the deviation of the center of the wheelchair from the center of the path taken every six inches. The performance measures examined were as follows:

1. Root Mean Squared (RMS) deviation
2. Maximum deviation
3. Number of center-line crossings
4. Position in forty-five degree turns
5. Position in ninety degree turns
6. Time taken to complete trial

Some adjustments were made to the data obtained from the study in order to make the results more meaningful. Due to a programming error in the software, the simulator stopped taking data in the middle of some of the trials. Table 1 depicts the trials in which one of the simulators malfunctioned and stopped taking data. When this occurred, it became impossible to derive meaningful performance measures for these specific trials. In order to run the

Table 1. Missing Data

Conditions (Speed x Direction x Device)	Subjects 1	2	3	4	5	6	7	8
low x ccw x wc								
low x cw x wc								
high x ccw x wc								
high x cw x wc								
low x ccw x on		X			X		X	
low x cw x on								
high x ccw x on			X	X				
high x cw x on				X				
low x ccw x bh								
low x cw x bh							X	
high x ccw x bh								
high x cw x bh								

low = low speed (2.2 mph)
high = high speed (3.3 mph)
cw = clockwise
ccw = counter-clockwise
wc = wheelchair
on = on simulator
bh = behind simulator

analysis of variance, estimates were made for the missing data. These estimates were the means of the scores for the other subjects in the same group under the same conditions. For instance, estimates for scores obtained by a disabled subject were made by taking the mean of the scores of the other disabled subjects under the same conditions.

Root Mean Squared Deviation

Root mean squared (RMS) deviation is defined as the square root of the mean of the squared deviations.

ANOVA. An ANOVA was run on the rms deviation using disability, device, speed, and direction as the main effects. The results of this analysis are shown in Table 2.

The significant main effects were device, with a significance level of 0.002, and speed, with a significance level of 0.023. The overall mean RMS deviation was 4.07 inches for low speed and 6.17 inches for high speed. The mean RMS deviation was 3.55 inches for the on simulator, 5.09 inches for the wheelchair, and 6.71 inches for the behind simulator.

There were two significant interactions which occurred in this analysis. The first significant interaction effect was disability by direction, with a significance of 0.020. As can be seen in Table 3, a Newman-Keuls test was performed on this interaction. This test detected no difference between clockwise and counter-clockwise directions for disabled users. However, scores for clockwise and counter-clockwise directions for non-disabled users were significantly different from each other and the scores for the disabled users.

Because the device by speed interaction approached the $p<0.05$ level of significance, a Newman-Keuls test was performed on its six groups. The results are seen in Table 3. The low speed by on simulator group was not significantly different from either the low speed by wheelchair group or the high speed by on simulator group. The low speed by wheelchair group was not significantly different from either the high speed by on simulator group or the low speed by behind simulator group. The low speed by behind simulator was not significantly different from the high speed by wheelchair group. Finally, the high speed by behind simulator group was significantly different from all of the other groups.

Table 2. List of F Tests for the ANOVA on RMS Deviation

Source	*df*	*SS*	*F*	*Prob*
Between Subjects				
Disability	1	168.65	4.35	0.082
Within Subjects				
Device	2	159.20	10.68	0.002*
Speed	1	105.29	9.17	0.023*
Dir	1	2.14	2.42	0.170
Dis x Device	2	41.58	2.79	0.101
Dis x Speed	1	10.65	0.93	0.373
Dis x Dir	1	8.66	9.83	0.020*
Device x Speed	2	18.43	3.83	0.052
Device x Dir	2	6.98	0.53	0.599
Speed x Dir	1	1.12	1.44	0.276
Dis x Device x Speed	2	2.42	0.50	0.617
Dis x Device x Dir	2	28.85	2.21	0.153
Dis x Speed x Dir	1	3.29	4.22	0.086
Device x Speed x Dir	2	.77	0.51	0.614
Dis x Device x Speed x Dir	2	5.52	3.64	0.058

Table 3. Newman-Keuls Tests for RMS Deviation

Device	*Mean*	
on	3.55	A
wc	5.09	B
bh	6.71	C

Disability x Dir	*Mean*	
non x ccw	3.34	A
non x cw	4.24	B
dis x cw	6.29	C
dis x ccw	6.59	C

Device x Speed	Mean	
low x on	3.11	A
low x wc	3.88	AB
high x on	4.00	AB
low x bh	5.23	BC
high x wc	6.31	C
high x bh	8.18	D

Note: Means with the same letter are not significant at $p<0.05$

Correlations. Correlation coefficients were calculated for the RMS deviation scores of the wheelchair and the two simulators. The results of these calculations are shown in Table 4. The correlation coefficients in the first column were generated by pairing each score obtained under a set of conditions with one device with the score obtained under the same set of conditions with another device. For instance, the score obtained by subject number one driving the wheelchair in low speed clockwise around the course would be paired with the score obtained by subject number one driving the on simulator in low speed clockwise around the simulated course.

The bi-directional correlation coefficients in the second column were generated using the means of the clockwise and counter-clockwise scores under the same sets of conditions. This averaging was performed to obtain a score which better represents a subject's true ability to drive a wheelchair or simulator. In order to look at the mean score, an assumption is made that the direction of turns made before and after a straight section of path does not significantly affect the performance in that straight section of path, particularly since the data obtained eighteen inches before and after a turn is not used to calculate the performance measure. If this assumption is correct, averaging the scores would be effectively the same as running each subject two times under each set of conditions and averaging the results in order to obtain a more reliable measure of performance.

It can be seen from Table 4 that higher levels of correlation were found when the means of clockwise and counter-clockwise trial were paired as opposed to when the individual scores were paired.

Table 4. Correlation Coefficients for RMS Deviation

Devices	Correlation for All Paired Scores	Correlation for Bi-Directional Scores
wc with on	0.4113	0.7293
wc with bh	0.6878	0.8050
on with bh	0.7432	0.9522

Maximum Deviation

ANOVA. A second performance measure was maximum deviation in inches from the center of the path. The results of an ANOVA run on this dependent variable can be seen in Table 5. The significant effects were found to be the main effects of device and speed and the interaction effect of disability by device. The overall maximum deviation for low speed trials was 12.14 inches. The maximum deviation for high speed trials was 17.18 inches. A Newman-Keuls test was performed on the main effect of device. As can be seen in Table 6, the wheelchair was not significantly different from the on simulator at $p<0.05$, but both were significantly different from the behind simulator. As seen again in Table 6, a Newman-Keuls test was performed on the disability by device interaction. None of the groups were significantly different from the others, except for the non-disabled users driving the behind simulator. This group was significantly different from all of the others at $p<0.05$.

Table 5. List of F Tests for ANOVA on Maximum Deviation

Source	*df*	*SS*	*F*	*Prob*
Between Subjects				
Disability	1	1022.14	5.08	0.065
Within Subjects				
Device	2	627.00	5.87	0.017*
Speed	1	611.30	10.16	0.019*
Dir	1	33.55	1.57	0.256
Dis x Device	2	590.57	5.53	0.020*
Dis x Speed	1	94.51	1.57	0.257
Dis x Dir	1	68.77	3.23	0.123
Device x Speed	2	156.73	3.41	0.067
Device x Dir	2	84.34	1.00	0.396
Speed x Dir	1	7.74	0.68	0.442
Dis x Device x Speed	2	123.27	2.68	0.109
Dis x Device x Dir	2	188.99	2.25	0.148
Dis x Speed x Dir	1	20.40	1.79	0.230
Device x Speed x Dir	2	28.45	0.93	0.419
Dis x Device x Speed x Dir	2	15.73	0.52	0.609

Table 6. Newman-Keuls Tests for Maximum Deviation

Device	*Mean*	
on	12.04	A
wc	13.81	A
bh	18.13	B

Disability x Device	*Mean*	
non x on	9.70	A
non x bh	11.47	A
non x wc	13.02	A
dis x on	14.37	A
dis x wc	14.61	A
dis x bh	24.78	B

Note: Means with the same letter are not significant at $p<0.05$

Correlations. The correlation coefficients were calculated for the maximum deviation scores obtained using the three devices. The results are displayed in Table 7. Again, for each device combination, two correlation coefficients are shown. The column first contains the correlation coefficient between all paired scores under the same set of conditions. The second column contains the correlation coefficient for the paired means of the clockwise and counter-clockwise scores under the same set of conditions. As seen with RMS deviation, the means of the clockwise and counter-clockwise scores were more highly correlated than the individual scores.

Table 7. Correlation Coefficients for Maximum Deviation.

Devices	Correlation for All Paired Scores	Correlation for Bi-Directional Scores
wc with on	0.1849	0.4577
wc with bh	0.4644	0.5509
on with bh	0.6060	0.7962

Number of Path Crossings

ANOVA. An ANOVA was run on the number of times the center of the path was crossed by the center of the wheelchair during a two lap run. Each crossing must have extended at least two inches from the center of the path in order to be counted. As seen in Table 9, no main effects and only a few interaction effects approached a level of significance. These interactions were disability x device, speed x direction, and disability x device x speed. Newman-Keuls tests were performed on the interaction effects which approached significance and failed to find any significant differences at the 0.05 level of significance.

Table 8. List of F Tests for ANOVA on Number of Path Crossings

Source	*df*	*SS*	*F*	*Prob*
Between Subjects				
Disability	1	42.67	1.20	.315
Within Subjects				
Device	2	9.00	0.30	0.746
Speed	1	0.38	0.04	0.855
Dir	1	9.38	0.57	0.480
Dis x Device	2	112.58	0.30	0.054
Dis x Speed	1	1.04	0.10	0.762
Dis x Dir	1	5.04	0.30	0.601
Device x Speed	2	21.00	0.91	0.429
Device x Dir	2	4.75	0.29	0.751
Speed x Dir	1	20.17	6.00	0.050*
Dis x Device x Speed	2	90.58	3.92	0.049
Dis x Device x Dir	2	13.58	0.84	0.456
Dis x Speed x Dir	1	0.67	0.20	0.672
Device x Speed x Dir	2	18.08	1.54	0.253
Dis x Device x Speed x Dir	2	8.58	0.73	0.501

Correlations. Correlation Coefficients were calculated for the number of crossings. The results are displayed in Table 9. As can be seen, the on simulator correlated negatively with the wheelchair, both when the individual scores were paired (-0.3438) and when the means of the bi-directional scores were paired (-0.4002). The behind simulator did not correlate very highly with the wheelchair in either case.

Table 9. Correlation Coefficients for Number of Path Crossings.

Devices	Correlation for All Paired Scores	Correlation for Bi-Directional Scores
wc with on	-0.3438	-0.4002
wc with bh	0.0331	-0.0632
on with bh	0.5636	0.6627

When correlation coefficients were calculated separately for low speed trials and high speed trials, interesting results were found. For low speed trials, the on simulator scores were correlated to the wheelchair scores with a correlation coefficient of -0.9228. However, high speed on simulator scores were positively correlated to high speed wheelchair scores with a correlation coefficient of 0.7480.

A plot of the low speed scores can be seen in Figure 5. As can be seen by the plot, at low speeds, subjects who tended to cross the center-line more often with the wheelchair, tended to cross it less often with the simulator. Interestingly, the non-disabled subjects, denoted by the letter "N" on the plot, tended to cross the line less with the simulator, possibly because it had less inertia and was easier to control. However, the disabled subjects, denoted

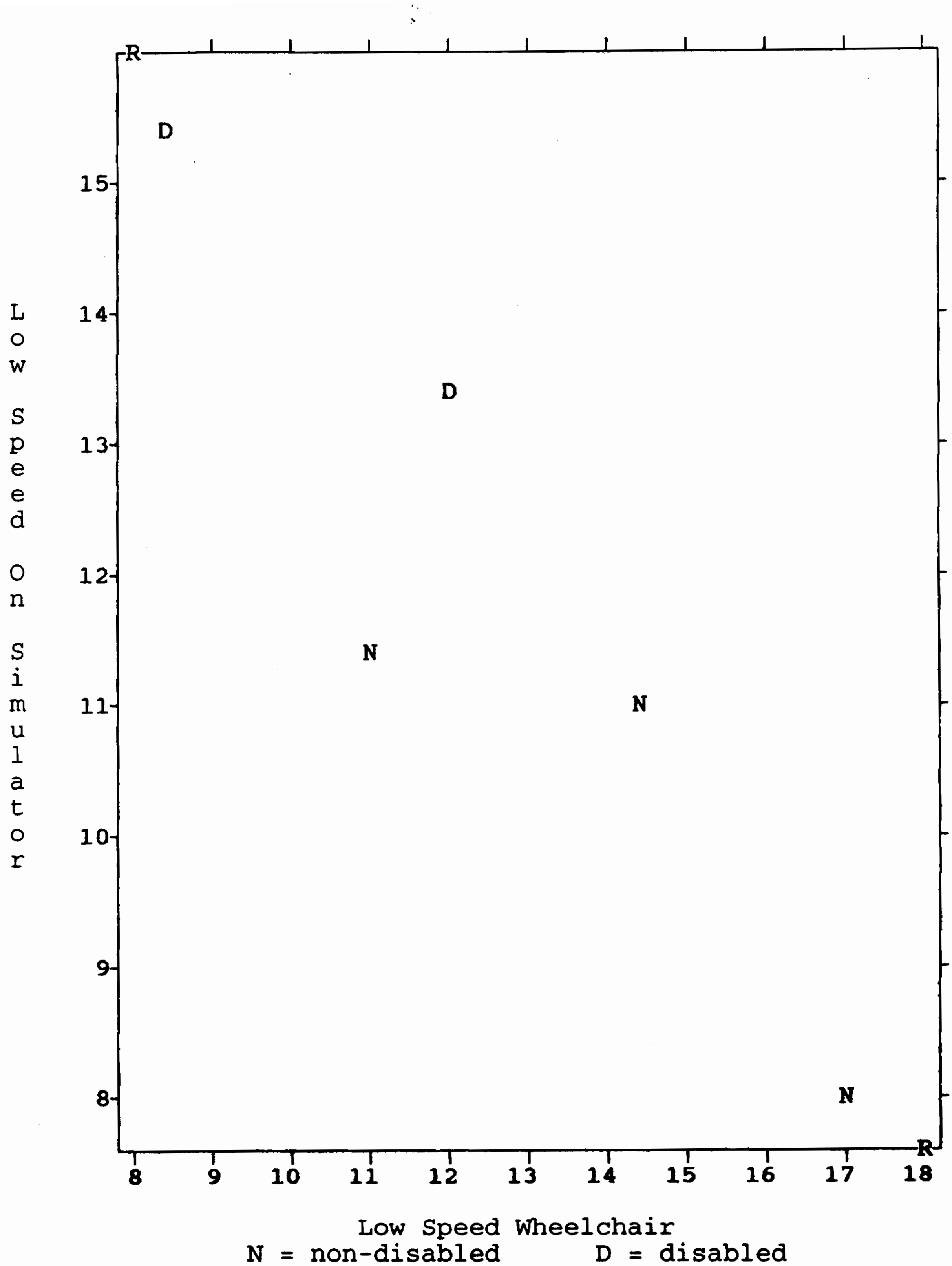


Figure 5. Here is a scatterplot of low speed on simulator number of path crossings scores with low speed wheelchair number of path crossings scores.

by the letter "D", who had more experience driving an actual wheelchair, crossed the center-line less in the wheelchair than in the simulator. Because the scores of subjects with missing data on either clockwise or counter-clockwise trials were not used in the calculation of this correlation, the negative correlation of -0.9228 is based on the performance of only five subjects.

A plot of the high speed wheelchair scores verus high speed simulator scores can be seen in Figure 6. Again, high speed on simulator scores were found to correlate to high speed wheelchair scores with a correlation coefficient of 0.7480.

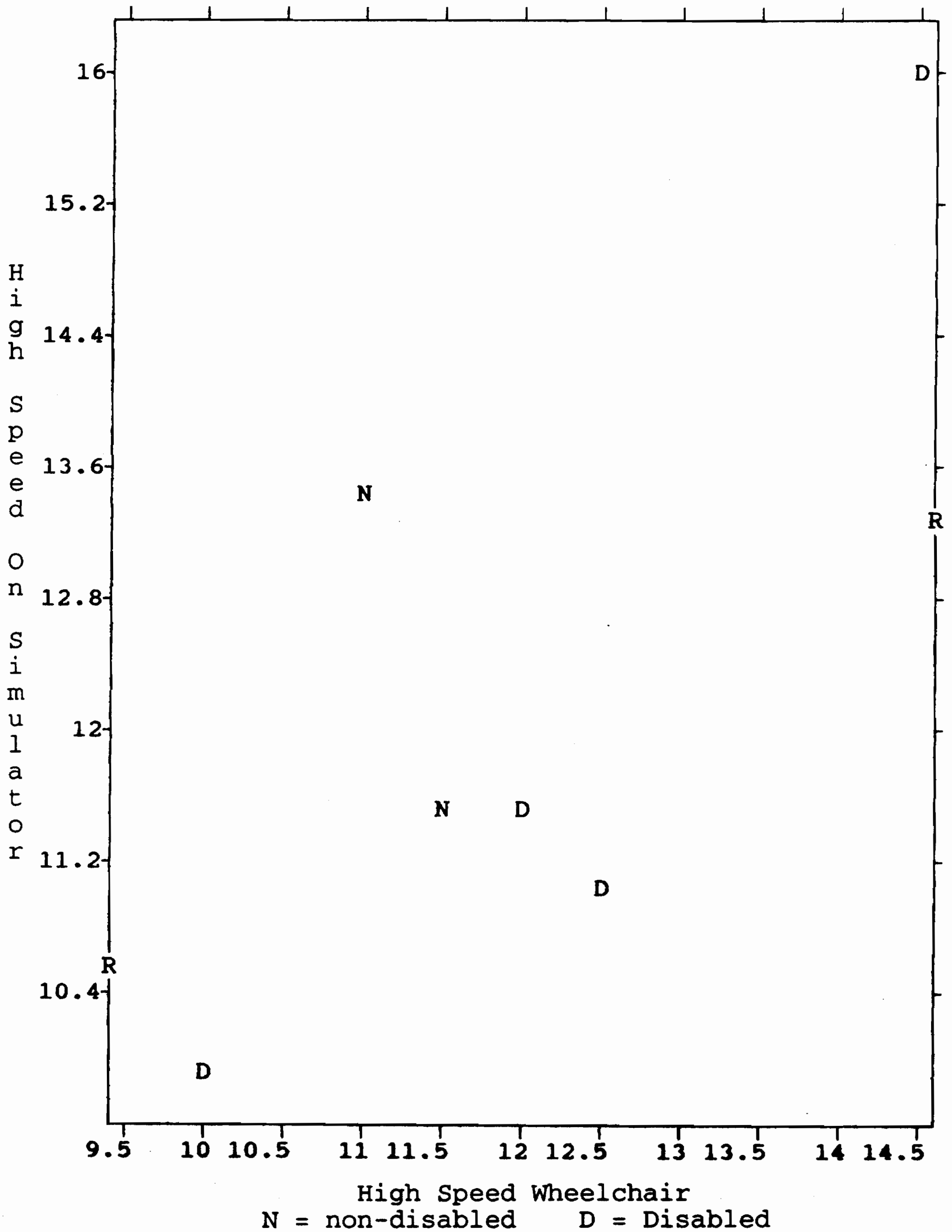


Figure 6. Here is a scatterplot of high speed on simulator number of path crossings scores with high speed wheelchair number of path crossings scores.

When the bi-directional scores were correlated for the behind simulator and the wheelchair, a correlation coefficient of 0.0632 was calculated. As with the on simulator, when the low speed scores for the behind simulator were correlated with the low speed scores for the wheelchair, a negative correlation coefficient of -0.4562 was found. The scores of seven subjects were used to produce this correlation. The plot of low speed behind simulator scores with low speed wheelchair scores can be seen in figure 7. A correlation coefficient of 0.3526 was calculated for the means of high speed behind simulator scores paired with the means of high speed wheelchair scores. A plot of these scores may be seen in Figure 8.

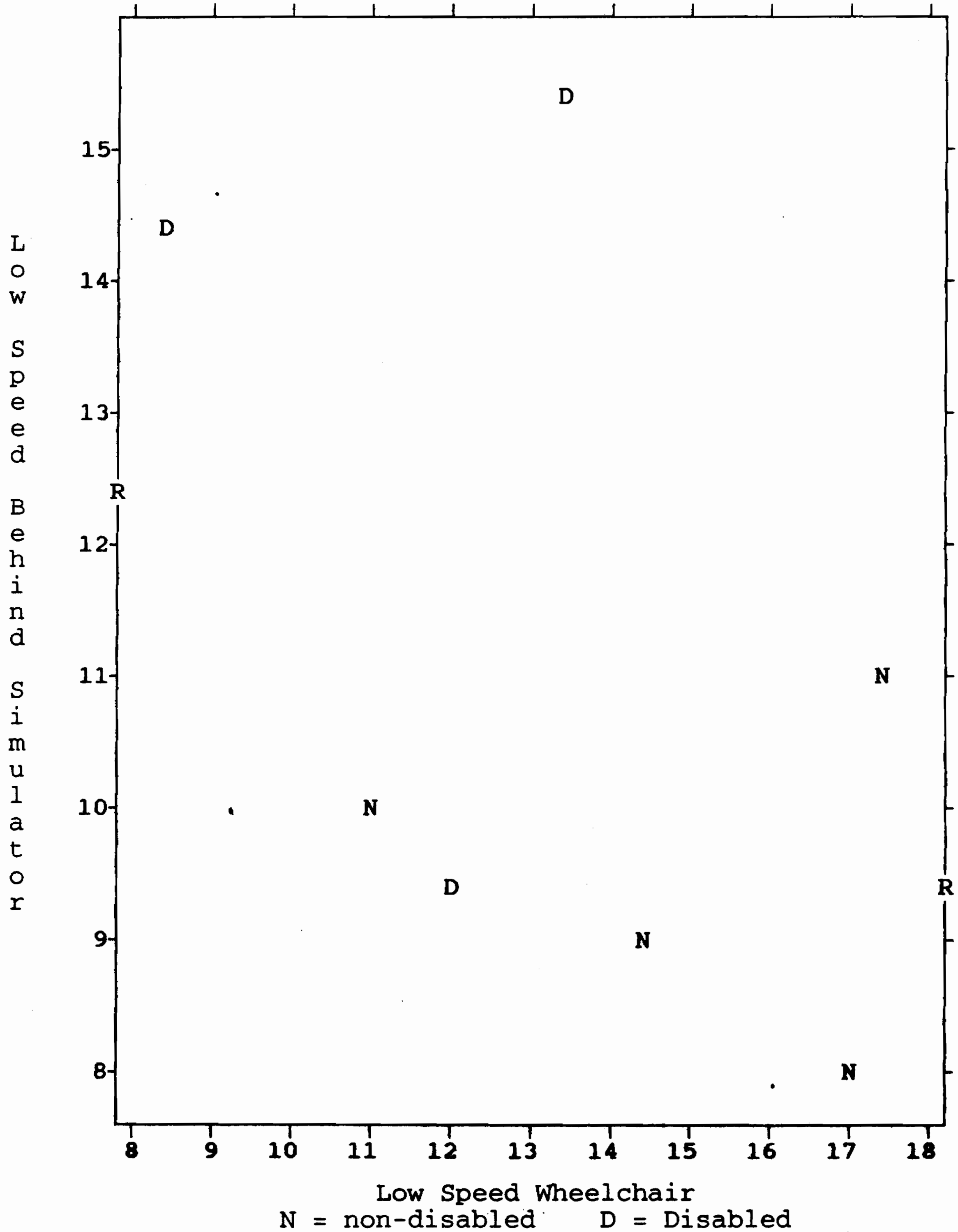


Figure 7. Here is a scatterplot of low speed behind simulator number of path crossings scores with low speed wheelchair number of path crossings scores.

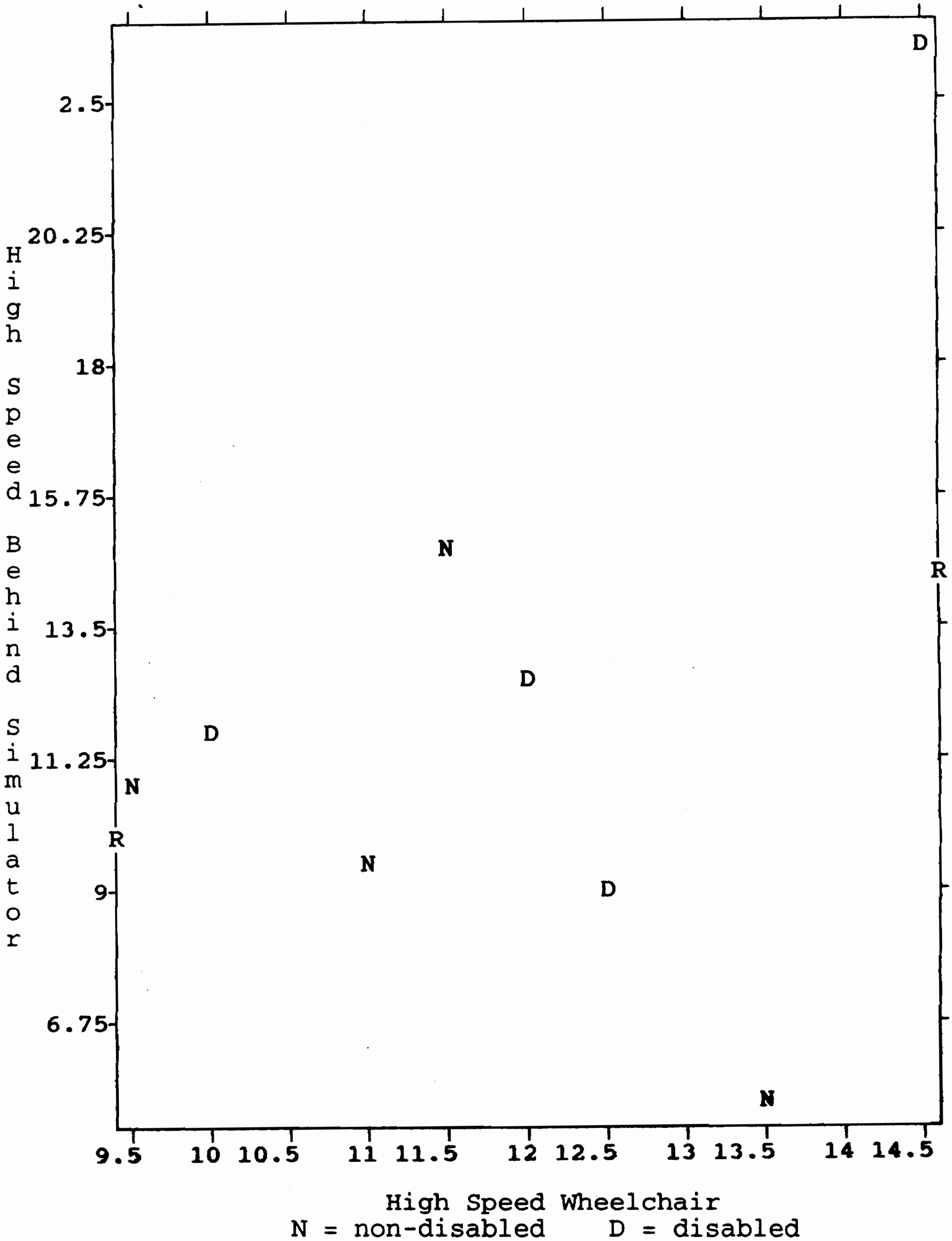


Figure 8. Here is a scatterplot of high speed behind simulator number of path crossings scores with high speed wheelchair number of path crossings scores.

Position in Forty-five Degree Turns

Two types of turns were required to complete the course. The first type was the forty-five degree turn. The position of the wheelchair in this type of turn is defined as the position of the center of the wheelchair in inches to the right of the path center-line along an axis which is perpendicular to the section of path preceding the turn and which crosses the intersection of the inside lines which define the turn. The axis along which the score is measured and a sample wheelchair position is illustrated in Figure 9.

ANOVA. An ANOVA was run on the position of the wheelchair and simulators in a forty-five degree turn. The results are shown in Table 10. As can be seen, there were no significant main effects, although the disability main effect approached significance ($p=0.059$). The only significant interaction was that of disability x device, which had a significance level of 0.006. As seen in Table 11, the only mean which differed significantly from the others at a 0.05 level of significance was the non-disabled users driving the behind simulator. The negative number for this mean score indicates that this group tended to cut the turns long. All other groups tended to cut the turns short.

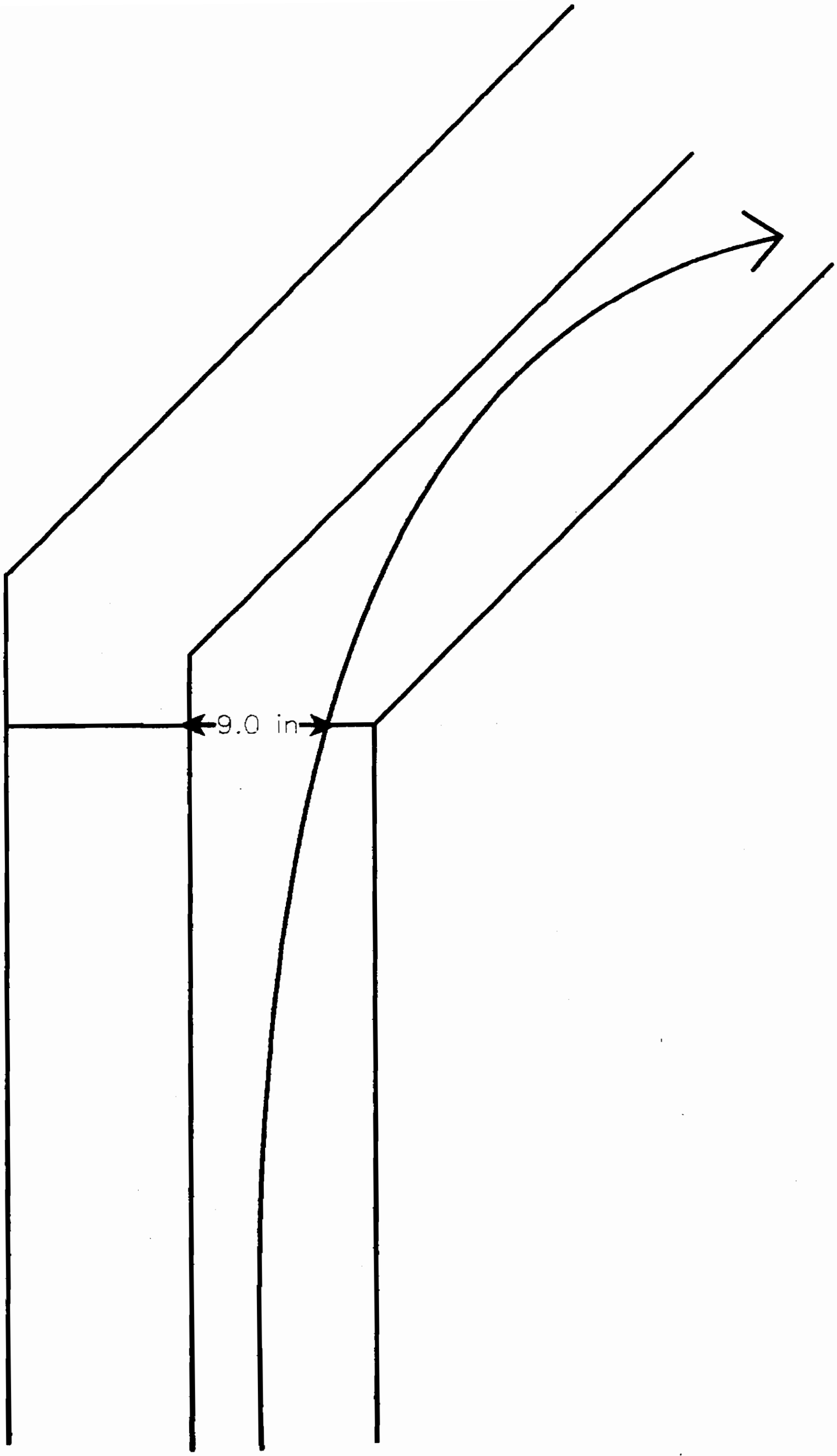


Figure 9. Position measurement is shown for forty-five degree turns.

Table 10 List of F Tests for ANOVA on Position in Forty-Five Degree Turns

Source	*df*	*SS*	*F*	*Prob*
Between Subjects				
Disability	1	447.29	5.42	0.059
Within Subjects				
Device	2	119.69	1.21	0.331
Speed	1	7.30	0.28	0.618
Dir	1	0.21	0.01	0.930
Dis x Device	2	794.11	8.05	0.006*
Dis x Speed	1	7.01	0.27	0.625
Dis x Dir	1	8.87	0.36	0.573
Device x Speed	2	139.08	2.38	0.135
Device x Dir	2	3.53	0.05	0.953
Speed x Dir	1	159.44	3.90	0.096
Dis x Device x Speed	2	68.11	1.16	0.345
Dis x Device x Dir	2	37.11	0.51	0.612
Dis x Speed x Dir	1	81.07	1.98	0.209
Device x Speed x Dir	2	145.02	2.24	0.149
Dis x Device x Speed x Dir	2	143.65	2.22	0.152

Table 11. Newman-Keuls Test for Position in Forty-Five Degree Turns

Disability x Device	*Mean*	
non x bh	-1.09	A
non x wc	6.73	B
dis x wc	6.89	B
non x on	7.67	B
dis x on	8.01	B
dis x bh	11.36	B

Note: Means with the same letter are not significantly different from each other at $p<0.05$

Correlations. Correlation Coefficients were calculated for position of the device in a forty-five degree turn and are displayed in Table 12. This table, in addition to presenting correlation coefficients for paired individual scores and paired means of clockwise and counter-clockwise scores, presents separate coefficients computed for paired clockwise scores and paired counter-clockwise scores. This extra step was taken because the performance measure of position in a right hand turn may be considered different from the performance measure of position in a left hand turn. Also, the subject may behave differently in right and left hand turns.

Table 12. Correlation Coefficients for Position in Forty-Five Degree Turns

Devices	Correlation for All Paired Scores	Correlation for Bi-Directional Scores
wc with on	0.1863	0.1636
wc with bh	0.0744	0.1127
on with bh	0.1955	0.5736

Devices	Correlation for Paired Clockwise Scores	Correlation for Paired Counter-Clockwise Scores
wc with on	-0.3603	0.3789
wc with bh	-0.1660	0.3957
on with bh	-0.1744	0.8260

Position in Ninety Degree Turns

The second type of turn used in the course was a sharp ninety degree turn. As shown in Figure 10, the measured position of the wheelchair in a ninety degree turn is defined as the distance that the center of the wheelchair is from the inside of the center-line of the section of path preceding the turn, measured along the inside line of the section of path following the turn.

ANOVA. An ANOVA was performed on the positions of the wheelchair and simulators in a ninety degree turn. As seen in Table 13, the only significant main effect was that of device. A Newman-Keuls Test, shown in Table 14, revealed that the scores for the behind simulator and the wheelchair were not significantly different from each other, but both were significantly different from the on simulator. The only significant interaction which was present was device by direction. As seen in Table 14, the position scores for the behind simulator driven clockwise were not significantly different from those of the wheelchair driven clockwise. Also, the scores of the on simulator driven clockwise were not significantly different from those of the on simulator driven counter-clockwise.

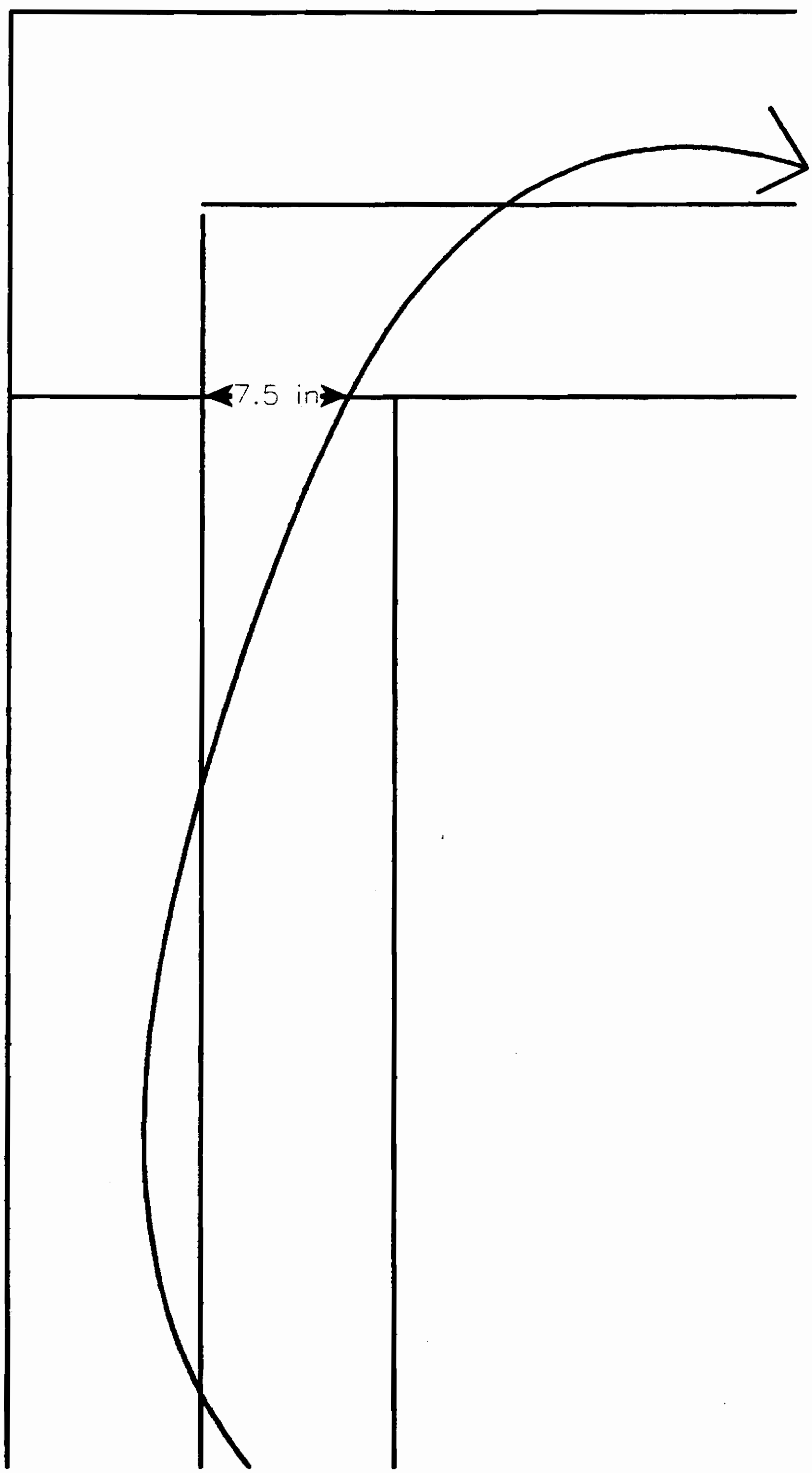


Figure 10. Position measurement is shown for ninety degree turns.

Table 13. List of F Tests for ANOVA on Position in Ninety Degree Turns

Source	*df*	*SS*	*F*	*Prob*
Between Subjects				
Disability	1	748.45	3.04	0.132
Within Subjects				
Device	2	2034.99	11.08	0.002*
Speed	1	1.60	0.04	0.845
Dir	1	3.90	0.16	0.701
Dis x Device	2	371.30	2.02	0.175
Dis x Speed	1	6.39	0.17	0.697
Dis x Dir	1	16.76	0.70	0.435
Device x Speed	2	57.72	1.41	0.282
Device x Dir	2	99.91	6.63	0.011*
Speed x Dir	1	13.58	0.93	0.372
Dis x Device x Speed	2	125.62	3.07	0.084
Dis x Device x Dir	2	25.50	1.69	0.225
Dis x Speed x Dir	1	3.51	0.24	0.642
Device x Speed x Dir	2	33.81	0.24	0.788
Dis x Device x Speed x Dir	2	43.37	0.31	0.738

Table 14. Newman-Keuls Tests for Position in Ninety Degree Turns

Device	*Mean*	
bh	6.32	A
wc	9.35	A
on	17.24	B

Device x Dir	*Mean*	
bh x ccw	5.10	A
bh x cw	7.54	B
wc x cw	8.23	B
wc x ccw	10.46	C
on x cw	16.53	D
on x ccw	17.96	D

Note: Means with the same letter are not significantly different from each other at $p<0.05$

Correlations. Pearson correlation coefficients were calculated for position in ninety degree turns. The coefficients are displayed in Table 15. As with the position in forty-five degree turns, correlations were calculated for all paired scores, paired means of clockwise and counter-clockwise scores, paired clockwise scores, and paired counter-clockwise scores.

Table 15. Correlation Coefficient for Position in Ninety Degree Turns

Devices	Correlation for All Paired Scores	Correlation for Bi-Directional Scores
wc with on	0.0035	-0.0240
wc with bh	0.1493	0.2319
on with bh	0.5365	0.8844

Devices	Correlation for Paired Clockwise Scores	Correlation for Paired Counter-Clockwise Scores
wc with on	-0.1294	0.0492
wc with bh	-0.0106	0.4676
on with bh	0.5698	0.5520

Completion Time

ANOVA. A final dependent variable used to compare performance on the wheelchair to performance on both of the simulators was the amount of time in seconds to complete two laps around the course. The results of an ANOVA performed on this variable appear in Table 17.

The main effect of device approached significance at $p<0.05$ with a level of significance of $p=0.052$. Because this was close to a level of significance of $p<0.05$, a Newman-Keuls test was performed. The results of this test appear in Table 17. As can be seen, there was no significant difference in time to complete two laps between the wheelchair treatment group and the on simulator treatment group. Also, time to complete two laps was not significantly different between the on simulator treatment group and the behind simulator treatment group. However, the behind treatment group differed significantly from the wheelchair treatment group with $p<0.05$.

The second significant main effect for the dependent variable of completion time is, as expected, speed. The mean score for low speed was 45.68 seconds and the mean score for high speed was 36.64 seconds.

The only significant interaction for the dependent variable of completion time is speed by direction. A Newman-Keuls test was performed on this interaction. The results appear in Table 17. As can be seen, the low speed scores in the clockwise direction were not significantly different from the low speed scores in the counter-clockwise direction. However, both high speed scores were significantly different from each other and the low speed scores at $p<0.05$.

Table 16. List of F Tests for ANOVA on Completion Times

Source	*df*	*SS*	*F*	*Prob*
Between Subjects				
Disability	1	118.81	0.31	0.600
Within Subjects				
Device	2	510.98	3.81	0.052
Speed	1	1962.04	64.24	0.000
Dir	1	42.67	4.33	0.083
Dis x Device	2	135.23	1.01	0.394
Dis x Speed	1	0.01	0.00	0.986
Dis x Dir	1	0.05	0.01	0.945
Device x Speed	2	61.44	1.18	0.340
Device x Dir	2	99.91	6.63	0.374
Speed x Dir	1	67.00	13.21	0.011
Dis x Device x Speed	2	6.58	0.13	0.882
Dis x Device x Dir	2	25.50	1.69	0.225
Dis x Speed x Dir	1	6.20	1.22	0.311
Device x Speed x Dir	2	1.38	0.05	0.956
Dis x Device x Speed x Dir	2	15.47	0.51	0.613

Table 17. Newman-Keuls Tests for Completion Times

Device	*Mean*	
wc	38.49	A
on	40.87	AB
bh	44.12	B

Speed x Dir	*Mean*	
high x cw	35.14	A
high x ccw	38.14	B
low x ccw	45.51	C
low x cw	45.85	C

Note: Means with the same letter are not significantly different from each other at $p<0.05$.

Correlations. Pearson correlation coefficients for completion time are shown in Table 18. The correlation coefficients were calculated both for all paired scores and for paired means of clockwise and counter-clockwise scores. In the latter case, the clockwise and counter-clockwise scores were averaged in order to give a score which better represents a subject's true wheelchair driving characteristics.

Table 18. Correlation Coefficients for Completion Time

Devices	Correlation for All Paired Scores	Correlation for Bi-Directional Scores
wc with on	0.6434	0.7657
wc with bh	0.4601	0.5417
on with bh	0.7206	0.7576

Subjective Rating

Following each trial involving a simulator, each subject responded to a set of nine bipolar rating scales. Each scale had seven intervals, each of which was assigned a number from one to seven, with low values corresponding to more positive perceptions (similar to wheelchair, easy to use, etc.,) and high values to more negative perceptions (not similar to wheelchair, difficult to use, etc.). The bipolar scales and results may be seen in Appendices C and D.

Within the nine bipolar scales were three pairs of scales which measured the users' perception of the simulator in turns and straight sections of path. The first pair measured ease of use in turns and straight sections of path. The second pair measured the degree of similarity between the simulator and the wheelchair in terms of the feel of driving. This rating, again, was taken for both turns and straight sections of path. The final pair measured the degree of realism of the control dynamics of the simulator relative to the actual wheelchair in turns and straight sections of path.

A Wilcoxin matched-pairs signed ranks test was performed on the first bipolar pair to determine if subjects perceived driving the simulators straight to be more difficult than making turns. As can be seen in Table 19, the subjects tended to perceive driving in straight sections of path to be easier than driving through turns for both the on simulator and the behind simulator. This difference was significant at $p<0.05$ for the on simulator and approached significance with $p=0.064$ for the behind simulator.

Table 19. Wilcoxin Matched-Pairs Signed-Ranks Test for Perceived Ease of Driving in Turns Versus Straight Sections of Path

On Simulator

Mean Rank	Cases	
8.50	2	- Ranks (Turns < Straight)
6.73	11	+ Ranks (Turns > Straight)
	3	Ties (Turns = Straight)
	16	Total
		Two Tailed P = 0.0464

Behind Simulator

Mean Rank	Cases	
8.50	3	- Ranks (Turns < Straight)
6.73	11	+ Ranks (Turns > Straight)
	2	Ties (Turns = Straight)
	16	Total
		Two-Tailed P = 0.0640

Note: Smaller ratings denote greater ease of driving.

A Wilcoxin matched-pairs signed ranks test was also performed on the first bipolar pair to determine whether one of the simulators was perceived to be easier to drive than the other, both in turns and on straight sections of path. As seen in Table 20, the on simulator was perceived to be easier to drive than the behind simulator at a level of significance of $p<0.05$ in both turns and straight sections of path.

Table 20. Wilcoxin Matched-Pairs Signed-Ranks Test for Ease of Driving the On Simulator Versus the Behind Simulator

Driving in Turns

Mean Rank	Cases	
4.00	2	- Ranks (Behind < On)
6.44	9	+ Ranks (Behind > On)
	5	Ties (Behind = On)
	16	Total
		Two Tailed P = 0.0262

Driving on Straight Sections of Path

Mean Rank	Cases	
4.00	1	- Ranks (Behind < On)
6.73	11	+ Ranks (Behind > On)
	4	Ties (Behind = On)
	16	Total
		Two-Tailed P = 0.0060

Note: Smaller ratings denote greater ease of driving.

The second pair of bipolar scales asked the subjects to rate the feel of driving the simulator compared to driving the actual wheelchair, both in turns and on straight sections. The results of a Wilcoxin sign test comparing turns to straight sections of path can be seen in Table 21. The feel of driving was perceived to be more similar to driving an actual wheelchair on straight sections than in turns. This difference was significant at $p<0.05$ for both the on simulator and the behind simulator.

Wilcoxin sign tests were also performed to determine if the feel of driving the on simulator was different from the feel of driving the behind simulator. These tests were performed for both turns and straight sections of path. As seen in Table 22, the on simulator and the behind simulator were perceived differently for straight sections of path at a level approaching significance (two-tailed $p = 0.0687$). However, there was not a significant difference between the feel of the two simulators when navigating turns.

Table 21. Wilcoxin Matched-Pairs Signed-Ranks Test for Perceived Similarity to the Wheelchair When Navigating Turns Versus Straight Sections of Path.

On Simulator

Mean Rank	Cases	
3.50	1	- Ranks (Turns < Straight)
6.44	9	+ Ranks (Turns > Straight)
	5	Ties (Turns = Straight)
	16	Total
		Two Tailed P = 0.0087

Behind Simulator

Mean Rank	Cases	
4.00	3	- Ranks (Turns < Straight)
7.33	9	+ Ranks (Turns > Straight)
	4	Ties (Turns = Straight)
	16	Total
		Two-Tailed P = 0.0342

Note: Smaller ratings denote greater similarity to wheelchair.

Table 22. Wilcoxin Matched-Pairs Signed-Ranks Test for Perceived Similarity to Wheelchair When Driving the On Simulator Versus the Behind Simulator

Driving in Turns

Mean Rank	Cases	
6.00	6	- Ranks (Behind < On)
9.33	9	+ Ranks (Behind > On)
	1	Ties (Behind = On)
	16	Total
		Two Tailed P = 0.1728

Driving on Straight Sections of Path

Mean Rank	Cases	
5.88	4	- Ranks (Behind < On)
8.15	10	+ Ranks (Behind > On)
	2	Ties (Behind = On)
	16	Total
		Two-Tailed P = 0.0687

Note: Smaller ratings denote greater similarity to wheelchair.

The final pair of bipolar scales measured how realistic the response of the simulators were to a control input, as compared to the actual wheelchair. One scale measured the users' perception of navigating straight sections of path and the other scale measured users' perception of turns. The results of a Wilcoxin sign test are given in Table 23. The difference between perceived realism of response in turns and perceived realism of response in straight sections did not approach a level of significance with $p<0.05$ for either the on simulator or the behind simulator.

Table 24 shows the results of a Wilcoxin sign test comparing realism of response of the on simulator and the behind simulator. The comparison was made both for straight sections and turns. There was no significant difference in the subjects' responses describing realism in turns. The difference in perceived realism on straight sections of path, however, approached significance (two-tailed $p = 0.0736$).

Table 23. Wilcoxin Matched-Pairs Signed-Ranks Test for Perceived Realism of Response When Navigating Turns Versus Straight Sections of Path

On Simulator

Mean Rank	Cases	
5.10	5	- Ranks (Turns < Straight)
6.75	6	+ Ranks (Turns > Straight)
	5	Ties (Turns = Straight)
	16	Total
		Two Tailed P = 0.5049

Behind Simulator

Mean Rank	Cases	
5.88	4	- Ranks (Turns < Straight)
4.30	5	+ Ranks (Turns > Straight)
	7	Ties (Turns = Straight)
	16	Total
		Two-Tailed P = 0.9057

Note: Smaller ratings denote greater realism.

Table 24. Wilcoxin Matched-Pairs Signed-Ranks Test for Perceived Realism of Response When Driving the On Simulator Versus the Behind Simulator

Driving in Turns

Mean Rank	Cases	
7.75	6	- Ranks (Behind < On)
8.17	9	+ Ranks (Behind > On)
	1	Ties (Behind = On)
	16	Total
		Two Tailed P = .4432

Driving on Straight Sections of Path

Mean Rank	Cases	
6.00	4	- Ranks (Behind < On)
8.10	10	+ Ranks (Behind > On)
	2	Ties (Behind = On)
	16	Total
		Two-Tailed P = .0736

Note: Smaller ratings denote greater realism.

There were three other bipolar rating scales not related specifically to straight sections and turns. Rather, these scales are more useful in describing the subjects' overall impression of the simulators. The scales measure the subjects' perception of the simulators' realism of display, accuracy in predicting wheelchair performance, and usefulness in predicting wheelchair performance.

Table 25 shows the results of a Wilcoxin sign test on the perceived realism of the display. As can be seen, the on simulator was perceived to have a more realistic display at a significance level of $p<0.05$.

Table 25. Wilcoxin Matched-Pairs Signed-Ranks Test for Perceived Realism of Display of the On Simulator Versus the Behind Simulator

Mean Rank	Cases	
3.50	1	- Ranks (Behind < On)
5.72	9	+ Ranks (Behind > On)
	6	Ties (Behind = On)
	16	Total
		Two Tailed P = .0144

Note: Smaller ratings denote a more realistic display.

Table 26 displays the results of a Wilcoxin sign test on perceived accuracy in predicting wheelchair performance. As can be seen, there was no significant difference between the two simulators in terms of the subjects' perception of accuracy.

Finally, a Wilcoxin sign test was performed on the subjects' rating of the simulators' usefulness in predicting wheelchair performance. As can be seen in Table 27, there was no significant difference at $p<0.05$ between the ratings given the on simulator and the ratings given the behind simulator.

Table 26. Wilcoxin Matched-Pairs Signed-Ranks Test for Perceived Accuracy of the On Simulator Versus the Behind Simulator in Predicting Wheelchair Performance

Mean Rank	Cases	
3.50	3	- Ranks (Behind < On)
4.38	4	+ Ranks (Behind > On)
	9	Ties (Behind = On)
	16	Total
		Two Tailed P = 0.5541

Note: Smaller ratings denote greater ease of driving.

Table 27. Wilcoxin Matched-Pairs Signed-Ranks Test for Perceived Usefulness of the On Simulator Versus the Behind Simulator in Predicting Wheelchair Performance

Mean Rank	Cases	
5.00	3	- Ranks (Behind < On)
5.00	6	+ Ranks (Behind > On)
	7	Ties (Behind = On)
	16	Total
		Two Tailed P = 0.3743

Note: Smaller ratings denote greater ease of driving.

Subject Questionnaires

After the experimental sessions were completed, each subject was asked to respond in a narrative manner to a series of questions regarding the comparison of the simulators to the wheelchair. This questionnaire did not differentiate between the two simulators because the control dynamics of the two views were exactly the same.

The non-disabled subjects, the first four run in the study, often commented in some way on the simulator's lack of inertia. Subject number one said that "the wheelchair had more momentum in turning than the simulator." Subject number two said it "was easier to go around turns in the simulator - easier to compensate for your mistakes." The third subject said "The wheelchair had a jerkiness which affected how you moved while with the screen (the simulators) it was just hand/eye coordination.... The simulator was more fluid - wheelchair was more jerky. Otherwise, they were the same." Subject number four described how the simulator differed from wheelchair by saying "It didn't have enough momentum. Power off joystick caused real wheelchair to continue to roll. Compensation was easier on the simulator.... (It) seemed like speed was more controllable with the simulator." Subject number four also suggested that to make the simulators' control system more realistic the experimenter should add forward momentum. The subject did not sense any simulated angular momentum.

The disabled subjects, numbered five through eight, were more mixed in their responses regarding the control dynamics of the simulator. The fifth subject described the difference between the simulator and the wheelchair as follows. "On low speeds (the simulator was) similar. (On) high speeds the simulator was easier. The simulator was similar to my wheelchair on high and low speeds.... It responded realistically - was closer to a normal wheelchair than the control wheelchair." The sixth subject described the difference as follows. "It's hard to say - a little different - not all together different. It was harder to get back on the course (in the wheelchair) once off. The simulator was easier in that it didn't jerk you.... The simulator had slower reactions." The seventh subject, however, felt differently. He described the simulator as being " a lot different - both perspectives.... It was more responsive and a lot more delicate." In order to make the simulator respond more realistically, the seventh subject suggested "Figure in factor of casters turning. On simulator you could turn on a dime. In wheelchair you had to wait for it to turn." The eighth subject described the two simulators as follows. "The behind view was real hard and a lot different. The other (on simulator) was right on track.... The actual wheelchair controls would take off quicker than the simulator. The wheelchair was jerkier. Rear (behind) view seemed more sensitive. Momentum was pretty close."

Thus, three of the subjects stated that they felt that the simulators did not have as much momentum as the other wheelchair, another three stated that the wheelchair was more "jerky" than the simulator, one said that it was easier to compensate for mistakes in the simulator, and one said the simulator responded realistically. A complete list of subject responses can be seen in Appendix E.

Discussion

There were two general types of performance measures derived from the data which recorded the position of the wheelchair or simulators relative to the course. The first general type of performance measure described performance on straight sections of path and included RMS deviation of the center of the wheelchair from the center of the path, maximum deviation of the wheelchair from the center of the path, and number of times the center of the path was crossed.

The second general type of performance measure described position in turns. One such measure was position in ninety degree turns, and the other was position in forty-five degree turns. The final performance measure, time to complete a course, encompasses performance both on turns and straight sections.

Turns are discussed separately from straight sections of path for several reasons. First of all the performance measures describing turning behavior are fundamentally different from those describing performance driving on straight sections. Additionally, when navigating a turn, the subject is asked to perform a different task than when navigating a straight section of path. When making a turn, the subject must use somewhat limited information and make a decision regarding the appropriate moment and manner in which to make a turn. Because the turn is approached somewhat quickly, the timing of the subject greatly affects the measure. When navigating a straight section of path, the subject is essentially performing a second-order, ramp input, compensatory tracking task.

Several factors affect measures which describe performance of the simulators. Two such factors are the amount of mass of the device and the amount of power the device is able to exert. Together, these two factors provide the user with a visual feel for the momentum of the device. When a user supplies an input to the wheelchair, it takes some amount of time for the wheelchair to overcome inertia and reach a steady state of behavior. Thus, the wheelchair has unique acceleration and turning properties, which the simulators attempted to model.

The wheelchair has other properties which affect performance. In order to increase safety, the amount of power generated by the wheelchair motors in a turn is limited by the electronics of the wheelchair. Thus, the angular speed of the wheelchair in turns is limited. The simulators attempted to model this characteristic.

A third performance characteristic of the wheelchair which the simulators attempted to model was the amount of dead space in the joystick. The user had to push the joystick a certain distance past a neutral point in order for the wheelchair to move. This characteristic was also modeled by the simulator.

Two other factors which affect wheelchair performance are friction of the wheels on the ground surface and the effects of the angular position of the front casters on instantaneous straight and angular acceleration. These last two factors were assumed to be negligible under the set of conditions that would be used in the experiment. Because the wheelchair would be driven on a smooth, hard surface, at low speeds (2.2 and 3.3 mph), friction of the wheels against the floor would be high enough to reduce the effects of wheel slip to an negligible level, yet low enough to not restrict movement of the wheelchair. If the wheelchair were operated on a carpeted surface, this might not be the case. Because the user was not asked to back up, or change directions at low power, the effect of the angular positions of the front casters was assumed to be negligible in order to simplify calculations performed by the simulation software. Calculations were kept as simple as possible in order to optimize the speed with which the simulators responded to user input and provided visual feedback to the user.

As previously described, the amount of momentum simulated by the simulator was set using subjective methods, as the exact performance characteristics of the wheelchair being simulated were unknown.

There is some evidence that the degree of momentum agreed upon by the pre-experimental subjects may not have been enough to model accurately the actual wheelchair. In the responses to the subject questionnaires, the subjects generally felt that the simulators did not have enough momentum and that the wheelchair had a "jerky" motion which was not present in the simulators. It should be noted that because the simulators used were fixed based, subjects did not receive the vestibular sensations they obtained using the wheelchair. This lack of motion may have contributed to the subjects' reports of the simulators' lack of inertia. A listing of anecdotal responses is given in Appendix E.

Straight Sections of Path

On Simulator. Despite the subjective response that the simulators did not have enough momentum, performance measures obtained with the on simulator were similar to those obtained with the wheelchair. At low speed, the RMS deviation of the on simulator and the wheelchair were not significantly different (3.11 in. and 3.88 in., respectively). However, at high speed, the wheelchair had significantly greater RMS deviation (6.31 in.) than the on simulator (4.00 in.). This interaction may have been due to the difference in inertia between the simulator and the wheelchair. The momentum may have become more of a factor affecting performance at high speeds, when oscillations are more difficult to correct. At low speeds, the users response rate may have been sufficiently fast to compensate for the difference in momentum between the two devices. Despite the significant interaction, bi-directional RMS deviations for the on simulator and the wheelchair were reasonably highly correlated, with a correlation coefficient of 0.7293.

The difference in momentum did not seem to have a great effect on the maximum deviation performance measure, possibly because larger deviations were not caused by oscillations, but rather by judgement errors. The mean maximum deviation of the on simulator (12.04 in.) was not significantly different from that of the wheelchair (13.81 in.). The maximum deviations of the on simulator and the wheelchair produced a correlation coefficient of 0.4577.

While the mean number of path crossings for the on simulator (12) and the wheelchair (11.6) were not significantly different, it is not known whether this failure to find a difference is because the two devices behaved similarly in terms of oscillation frequency about the center-line, the measure lacked reliability due to its relatively rare occurance in a trial, or because this performance measure was not meaningful. For instance, no significant main effects were found for this measure. Although three interactions approached a level of significance, Newman-Keuls tests failed to find any specific differences.

The number of path crossings of the on simulator and the wheelchair were negatively correlated with a correlation coefficient of -0.4002. When high speed and low speed trials were looked at separately, correlation coefficients of 0.7480 and -0.9228, respectively, were found. Although these correlations were based on only six and five pairs of data, respectively, they were both significant at $p<0.05$. One possible explanation for the effect of speed on the correlation of on simulator and wheelchair scores is that at low speed experience in wheelchair driving enables one to control the wheelchair with fewer over-corrections. The non-disabled subjects, who tended to make more corrections in the wheelchair, found it easier to control the on simulator, which had less inertia and required less correction. However, at high speeds, both the simulator and the wheelchair became more difficult to drive. This hypothesis is supported by the ANOVA run on number of path crossings. While a Newman-Keuls test failed to find any specific interaction, the ANOVA performed on this performance measure indicated a significant disability by device by speed interaction effect.

The results found with the number of path crossings performance measure are difficult to interpret. It is not fully understood why this measure failed to yield any significant main effects or why the high negative correlation occurred. One problem with this measure is that it may have low reliability due to its relatively rare occurrence in a trial. It also may not be a meaningful measure. That is, it may not be conveying meaningful information about the manner in which subjects drove the wheelchair or simulators. Perhaps more appropriate measures could be derived from the positional data using spectral analysis techniques such as a Fourier transformation. It is not known whether the frequency distribution peaked at a certain frequencies, or was more uniformly distributed. If there were dominant frequencies, a measure which could be derived from the data is the primary frequency at which subjects tended to correct for error and oscillate about the center line.

Because most of the time spent during the trials was spent navigating straight sections of path, the completion times could be used to demonstrate how well the on simulator modelled the speed of the on simulator. Because the mean completion time for the on simulator (40.87 s.) was not significantly different from that of the wheelchair (38.49 s.), the on simulator was found to model the speed of the wheelchair well. Similarly, bi-directional scores taken with the on simulator correlated with a coefficient of 0.7657 with those of the wheelchair.

Behind Simulator. After each simulator trial, subjects answered bipolar rating scales which rated the device in terms of ease of driving, similarity to wheelchair, and realism of control response. Wilcoxin Matched-Pairs Signed-Ranks Tests indicated that the subjects felt the on simulator performed better than the behind simulator on each of these dimensions. Although the response dynamics of the on simulator and the behind simulator were identical, the visual perspective offered by the behind simulator made it more difficult to use. This may be because the user saw the simulated wheelchair position from a perspective which tended to exaggerate the amount of correction needed. It should be noted that the response dynamics of the behind simulator were set to match those of the on simulator. Because the on simulator dynamics were set using subjective means by pre-trial subjects, there may have been an experimental bias in favor of the on simulator.

While the mean low speed RMS deviation for the behind simulator (5.23 in.) was not significantly greater than that of the wheelchair (3.88 in.), at high speeds the mean behind simulator RMS deviation (8.18 in.) was significantly greater than that of the wheelchair (6.31 in.). The unusual visual perspective of the subject using the behind simulator may have placed a larger mental work load on the subject. As discussed by McCormick and Sanders (1982), an increased load of stimuli increases the effect of the speed of stimuli on a subject's error rate. That is, a larger load may not have a great affect on errors when a task is performed at low speeds, but may cause the rate of errors to increase more sharply when the speed stress is increased. Despite the significant device by speed interaction, the bi-directional RMS deviation scores of the behind simulator and the wheelchair produced a high correlation coefficient of 0.8050.

Interestingly, the unusual perspective of the behind simulator had a greater detrimental effect on the performance of the disabled subjects, as seen in the device by disability interaction of the maximum deviation scores. While the mean scores of the non-disabled subjects driving the behind simulator and wheelchair and the disabled subjects driving the wheelchair were all similar (between 11.47 and 14.61 inches), the mean maximum deviation for the disabled subjects driving the behind simulator (24.78 in.) was much greater. Despite this interaction, the maximum deviation scores of the behind simulator and the wheelchair were somewhat correlated, with a correlation coefficient of 0.5505.

Two possible explanations may account for the disability by device interaction. First, it is possible that a transfer of training effect took place which enabled the disabled users to control the on simulator better. Because the behind simulator was foreign, no transfer of training occurred. Thus, the disabled users drove the behind simulator in much the same way that they would have driven it had they never driven an actual electric wheelchair. In fact, a poor level of performance may have occurred driving the on simulator, if the disabled users had never driven an electric wheelchair. The other possible explanation is that the experience driving electric wheelchairs did not influence performance driving the on simulator, but rather an interference effect took place which reduced performance using the behind simulator. That is, if the disabled subjects had never driven electric wheelchairs, they might have performed at a level comparable to the non-disabled subjects using both the on simulator and the behind simulator. The most probable explanation for the interaction effect, however, is that both transfer of training and interference effects were present.

The number of path crossings, using the behind simulator and the wheelchair, was not significantly different. As with the on simulator, it is not known if this is a meaningful performance measure. There was no significant correlation between the scores of the two devices.

The perceived difficulty in driving the behind simulator caused the subjects to drive it more slowly than the wheelchair. Although the mean completion time for the behind simulator (44.12 s.) was only 2.38 seconds longer than that of the wheelchair, this difference was found to be statistically significant. The completion times for the behind simulator correlated with those of the wheelchair with a correlation coefficient of 0.5417.

Turns

The two types of turns used in this study were sharp forty-five degree turns and sharp ninety degree turns. Unlike data collection on straight sections of path, there was only one data point taken for each turn. This measure was the deviation from the center line along a line which was perpendicular to the path at the beginning of the turn.

Several factors affected how the simulators made the turns. The fidelity with which the simulator modelled the wheelchair in terms of speed, turn-limiting, and momentum was one such factor. Another factor was the limitation of the display in terms of providing the user with a proper perspective and window of view. The display attempted to model the view that user of an average height would see looking through a window about fourteen inches from his or her face. This view, of course, would severely limit the amount of peripheral information available to the users.

The analysis of the results of the bipolar rating scales indicates that the subjects perceived both simulators to be more similar to driving the wheelchair on straight sections than on turns. This difference is thought to be due to the display limitations rather than the response dynamics of the simulators. For instance, while the simulator users had a preview of the track ahead when driving on straight sections, they could not see much of the track ahead when making a sharp turn. This limitation, which was more pronounced during ninety degree turns than forty-five degree turns, of course, was not present when driving the actual wheelchair. The rated perceived realism of response, as indicated on the bipolar rating scales, for both simulators on turns was not found to be different than on straight sections.

On Simulator. The mean position in forty-five degree turns for the on simulator (7.84 in.) was not significantly different from that of the wheelchair (6.81 in.). However, the bi-directional scores for the on simulator and the wheelchair were not well correlated. Therefore, in general, while the on simulator tended to perform in a similar manner to the wheelchair in making forty-five degree turns, it did not appear to be useful in predicting an individual's wheelchair performance at a certain speed relative to other speeds or subjects. Interestingly, speed did have not a significant effect on the position at which subjects entered forty-five degree turns.

Due to display limitations, subjects tended to make the ninety degree turns significantly earlier with the on simulator (17.24 in.) than the wheelchair (9.35 in.). One reason for turning early in the on simulator is that if the subject waited for too long, he would lose sight of the course. In fact, only a tiny portion of the course would be visible if the driver of the on simulator made the turn with little deviation from the course. Once the course was off the screen, the user would find it difficult to navigate the simulator to get back on course. To avoid this problem, the subjects may have turned early. This limitation would not be so extreme for forty-five degree turns, as the driver would still be able to see much of the course in front of the simulated wheelchair. Of course, the driver of the wheelchair would only have to turn his head to observe his position relative to the course to correct for any deviation.

As with forty-five degree turns, mean bi-directional user positions entering ninety degree turns did not correlate well with those of the wheelchair.

Behind Simulator. Subjective response to a bipolar rating scale indicates the on simulator was perceived to be easier to drive than the behind simulator in turns. However, from the rating scales, no significant difference was found in perceived similarity to the wheelchair or realism of response between the two simulators.

The original purpose for the development and testing of the behind simulator was to determine if information concerning the position of the rear wheels with respect to the course would enable the users to make turns in a manner more closely resembling performance in a wheelchair, given that wheelchair users can look down and see their relative position.

The ability to see position relative to the course had a great affect on the way non-disabled subjects made forty-five degree turns. An ANOVA run on this performance measure indicated that the only significant effect was that of the disability by device interaction. A Newman-Keuls test found that only the non-disabled subjects' mean scores with the behind simulator was significantly different from the mean scores under the other combination of conditions. This difference was notable, however. The non-disabled subjects driving the behind simulator produced a mean score of -1.09 inches. The negative sign indicates that this group tended to cut the turns long. That is, they tended to stay to the outside of the turn as they went into it, rather than to make the turn early, as did all other combinations of subjects. The disabled subjects tended to make the turn early with the behind simulator. In fact, this group had a mean score of 11.36 inches, which was the highest mean score observed for this interaction.

There are several possible explanations for this effect. With the behind simulator, the user saw the position of the rear wheels with respect to the course. Therefore, the user had information about his position which was not readily available from the other two devices. The non-disabled user was able to stay on the course more accurately when making the forty-five degree turns with the behind simulator. The disabled user, however, was not able to, or did not control the device as accurately in a turn for several possible reasons. First of all, due to the visual perspective, the behind simulator was quite different from the wheelchair to drive. Experience driving the wheelchair might have interfered with the ability to drive the simulator. Or perhaps the disabled subjects had a slower reaction rate or a lesser degree of fine hand control than the non-disabled subjects. Even though they had more visual information driving the behind simulator, they might have found the behind simulator more difficult to control around turns and compensated by anticipating a turn and turning earlier. The non-disabled subjects, however, were able to turn at the last possible moment. It is important to note that if the user drove off the end of the course with the simulator, the user would no longer be able to see the course. Because making a turn and getting back on course would be difficult when the course is no longer on the display, the disabled users may have chosen to be conservative and cut the turn early.

The ability of subjects to see their rear wheels with respect to the course tended to make them wait longer before making a turn in the behind simulator than in the on simulator. Again, in the on simulator, a subject making a turn with little deviation from the course would nearly lose sight of it. Therefore, subjects tended to be conservative and make ninety degree turns early in the on simulator. The behind simulator did not have this extreme limitation. For this reason, subjects driving the behind simulator tended to make ninety degree turns which were similar to those made in the wheelchair. The mean position entering a ninety degree for the behind simulator (6.32 in.) was not significantly different from the mean position for the wheelchair (9.35 in.).

The bi-directional positions in ninety degree turns for the behind simulator and the wheelchair did not correlate well with each other. Therefore, while the mean positions were not found to be significantly different, the behind simulator was not found to be a good predictor of an individual's performance in a wheelchair at a given speed relative to other speeds or users.

Future Research

Selection of Performance Measure. While the on simulator and the behind simulator often yielded performance measures which were not significantly different from those of the wheelchair, several differences were observed. These differences can often be explained by lack of simulator response fidelity and display limitations. In some instances, the relatively small number of measures taken per trial, and the lack of correlation between the simulator and the wheelchair scores raise the question of performance measure reliability. For instance, subjects navigated forty-five degree turns only four times per trial. Four resulting measurements were averaged in order to determine the position in forty-five degree turn dependent variable. Given that there might be a large amount of variance in turn navigation, this performance measure might not be highly reliable.

It may also be useful to examine performance measures describing user input to the devices. Such measures might include response frequencies and number of joystick reversals.

Simulated Response Dynamics. As seen in Table 28, the bi-directional scores obtained with the on simulator and the behind simulator generally correlated more highly with each other than with the wheelchair. The fact that they often correlated with each other makes it difficult to dismiss the measures as unreliable. It also suggests that the response dynamics of the simulators play a large role in enabling the simulators to predict performance on another device. Even though the visual perspectives given by the two simulators were quite different, the relative performance of a subject at a given speed on one simulator was somewhat predictive of his performance on the other simulator at the same level of speed.

Table 28. Summary of Bi-Directional Performance Measure Correlations

Score	WC-ON	WC-BH	ON-BH
RMS DEVIATION	0.7293	0.8050	0.9522
MAX DEVIATION	0.4577	0.5509	0.7962
NO. of CROSSINGS	-0.4002	-0.0632	0.6627
45 DEG. TURNS	0.1636	0.1127	0.5736
90 DEG. TURNS	-0.0240	0.2319	0.8844
COMPLETION TIME	0.7657	0.5417	0.7576

Because the simulators were better performance predictors of each other than the wheelchair, it is hypothesized that a simulator could be made to be a better performance predictor of the wheelchair if it were designed to model wheelchair performance more accurately. In order to do this, the response dynamics of a wheelchair would have to be known more accurately. It is suggested that future research incorporate a simulator that models wheelchair performance more faithfully.

Alterations to Track. In general, the on simulator yielded better results than the behind simulator. As indicated on the bipolar rating scales, the on simulator was perceived by subjects to be easier to control on straight sections and in turns, more similar to the wheelchair on straight sections, and more realistic in response on straight sections. In addition, subjects felt the display on the on simulator was more realistic. Except on the execution of sharp ninety degree turns, the on simulator yielded mean performance measures which tended to be more similar to those of the wheelchair than the behind simulator. Neither simulator had a decided advantage in yielding bi-directional scores which correlated highly with those of the wheelchair.

The only area in which the behind simulator tended to yield better results than the on simulator was in making ninety degree turns. However, the ninety degree turn performance measure may not have much construct validity in the real world. While people who drive wheelchairs often have to make sharp turns around obstacles, they rarely do so at full speed. As one subject with a disability reported, it is more realistic to not make sharp turns. Another suggested the use of curves instead of corners.

The use of gradual bends instead of sharp corners would have several advantages in future research. First of all, except in tight quarters, it is more similar to the manner in which people operate wheelchairs. Second, gradual bends would allow the user to see a preview of the track ahead using the on simulator. That is, subjects would not nearly lose sight of the track when making sharp turns. Performance would not be affected by the fear of running off the track and having difficulty getting back on due to a temporarily blank display. Also, interpretation of the results would be simplified as the task would essentially be a compensatory tracking task that did not require decisions to be made regarding the timing of turns. Finally, the same performance measures as those describing behavior on straight sections of path could be used. Thus, behavior on turns and straight sections could be more directly compared and the results could be more easily interpreted.

Procedural Flaws. The execution of the study could also be improved upon in future research. First of all, programming errors existed in the software which caused the simulators to stop taking data in a number of cases. Therefore, missing data had to be estimated. Future research should only be undertaken when the simulation packages have been thoroughly pre-tested. Second, a larger number of subjects should be used. The number of disabled subjects was limited due to geographical and time constraints. However, the study could be criticized for failing to find statistical differences with ANOVAs because of a lack of power. That is, with a small sample size, there is a greater risk of a type II error. The accepting the null hypothesis that the distribution of any given performance measure obtained from a simulator is the same as the distribution of the corresponding performance measure obtained from the wheelchair does not necessarily prove that they are the same.

Measurement Issues. Perhaps a different approach should be taken in future studies for the statistical analysis of the performance measures. Even with a very large sample size, it is not reasonable to expect that the simulator would yield the exact same performance measure results as the wheelchair. Even if the results were very close, there would be some difference. If this difference were small, the two scores might be considered to be effectively equivalent. For instance, the simulator would be considered to have validity if the mean scores on the performance measures were within 0.25 inches of those of the wheelchair. The simulator might even be considered to be valid if the scores were within a larger range of those of the wheelchair. It is important that an acceptable range of difference be defined such that if the true population difference between the simulator performance measures and the wheelchair performance measures fall within that range, the simulator is considered valid.

In order to conduct a study based on effective equivalence, for each subject, a performance measure would be derived from positional data taken from the simulator and the wheelchair. The difference between the measures taken from the two devices would then be recorded. Once all of the subjects are run, a confidence interval would be computed for the differences. Hopefully, the results would indicate that one could be ninety-five percent confident that the true mean difference is within a range sufficiently close to zero that the simulator would be considered valid for the set of conditions under which the performance measures were taken.

The method described above would limit the study to a one dimensional design and thus not give the amount of information given by an ANOVA. Thus, a trade off would exist between knowing about interactions, such as how experience in a wheelchair affected the manner in which the simulator modeled performance, and statistically showing that the difference between the simulator and the wheelchair is acceptable. However, the study could incorporate a number of parallel studies such that confidence intervals could be calculated for a number of conditions. Additionally, much of the information obtained by the ANOVA s in this study was extraneous to the validation of the simulator. For instance, while it is interesting to know that an increase in speed caused a higher RMS deviation, this information was not critical to validate the simulator.

Conclusion

This study involved the statistical validation of two wheelchair simulators. Although the simulators were developed to model a wheelchair which was used in the study as a control, there is some evidence that the simulators did not model wheelchair response dynamics faithfully. For instance, many subjects reported that the simulators did not have enough inertia.

Despite this deficiency, the on simulator yielded performance which were generally not significantly different from those of the wheelchair in straight sections of path. While RMS deviation was found to be statistically different, the mean difference was only about 1.5 inches. The straight section performance measures were reasonably well correlated between the on simulator and the wheelchair.

The behind simulator was generally felt to be more difficult to control than the on simulator. On straight sections, it yielded RMS deviations which, though statistically significant, differed from the wheelchair by only about two inches. The maximum deviation of the behind simulator, however, was quite a bit higher than that of the wheelchair.

On ninety degree turns, the on simulator was difficult to use because the subjects nearly lost sight of the track ahead if they made a turn defined by the course. For this reason, subjects tended to make the turns early. This was not a problem on forty-five degree turns. However, the simulator turn positions did not correlate well with those of the wheelchair.

Subjects with disabilities used the behind simulator differently than subjects without disabilities on forty-five degree turns. The non-disabled subjects tended to use the wheel position information to stay closer to the boundaries of the course. Mean positions in ninety degree turns undertaken with the behind simulator were not significantly different from those navigated in the wheelchair. The bi-directional turn positions in the behind simulator did not correlate well with those of the wheelchair.

In general, the bi-directional scores taken from one simulator correlated more highly with those of the other simulator than those of the wheelchair, even though the visual perspectives of the two simulators were radically different. The fact that the two simulators produced scores which were more highly correlated with each other than to those of the wheelchair suggests that a more dynamically accurate simulator would yield results which were even more similar to those of the wheelchair.

Because most high speed wheelchair use occurs on straight path or gradual turns, simulator tests in which the user is instructed to follow a course quickly should incorporate gradual turns and bends. Most sharp turns would be navigated at slower speeds and would require different navigational skills. It is possible that a simple small-screen simulator may not have as much utility in predicting how a user would be able to navigate sharp turns around obstacles due to visual positional feedback limitations. Because of this drawback, the fact that the on simulator yielded results which were better than the behind simulator on straight sections of the course, and the general lack of user acceptance to the behind simulator, it is felt that further research should incorporate a visual perspective of being in the wheelchair.

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Appendix A. Introduction and Informed Consent

Hello, and welcome to the Rehabilitation Engineering Assessment Lab. Today, you have the opportunity to participate in our research on the development of an electric wheelchair simulator. The simulator is being developed to provide therapists with more information when prescribing electric wheelchair controls (such as a joystick or sip and puff tube). The simulator may be used for the testing of various controls by a wheelchair user in order to evaluate which control is most suitable. The simulator may also be used for training a wheelchair user to use a new control. The simulator can automatically collect information on how a person performs with a given control while the person is driving with it.

Before participating in this experiment, you will be required to transfer into the wheelchair provided by the lab. If you need assistance, the experimenter and the assistant will assist you according to your instructions. In this experiment, you will drive an electric wheelchair around a course laid out in tape in a large room. You will also drive a simulator around a similar course. The simulated course will appear on a computer screen. You will be allowed to practice each task until you feel comfortable with it before performing the task as part of the experiment. The actual wheelchair which you will drive around the tape course is provided by the lab. It is important that you use that one because the simulator is set up to behave like it. You will be allowed to practice driving the wheelchair in the center of the room so that you can get the feel of it and to ensure that you feel comfortable driving it. The wheelchair has been tested to ensure that it will not tip over.

You will get a break after each task. During this time you may visit the restroom, get a drink of water, or just relax. Water is provided at the test site for your convenience. The experiment will begin again when you are ready. If for any reason you feel uncomfortable at any time during the experiment, you may inform the investigator and the experiment will be terminated. However, please note that the research team would appreciate your cooperation in completing the full experiment, if you can, so that a full set of data may be obtained.

As a participant in this study, you have certain rights. These rights will now be explained to you, and you will be asked for a signature, indicating that you consent to participate in the research.

1. As mentioned, you have the right to discontinue participating in the experiment at any time, for any reason. If you decide to terminate the experiment, inform the experimenter and he or she will pay you for the portion of time you have participated.

2. You have the right to inspect your data and withdraw it if you choose. In general, the data are gathered, processed, and analyzed after a subject has completed the experiment. At this time, all identification information will be removed and there will be no way to associate your data with you. This is to insure complete anonymity. Therefore, if you wish to withdraw your data for any reason, you must do so immediately after your participation is completed.

3. You have the right to be informed of the overall results of the experiment. If you wish to see a synopsis of the results, include your printed name and address (three months hence) with your signature below. The experimenter will be pleased to take down that information for you if you wish. If you should then like further information, you may contact the Human Factors department and a full report will be made available to you.

There are two small risks to which you will expose yourself in this experiment:

1. If you are disabled, there is the slight risk of a fall in transferring to or from the electric wheelchair to be used in the experiment. This risk should be no greater than that associated with a transfer under normal conditions to your own wheelchair; and as indicated, we will follow your instructions in getting you transferred.

2. There is the slight risk of a collision of the electric wheelchair with one of the walls of the experimental

room. This risk will be minimized by training you first in the center of the room. Only after you demonstrate proficiency, will you be permitted to drive along the normal course. In addition, this course is a reasonable distance from any of the walls, so there is tolerance for error.

This experiment is expected to last about one hour, thirty minutes, but may vary slightly from this duration. You will be paid $5.00 per hour for the time you participate.

Detailed instructions will follow your reading and signing of this informed consent form. If those instructions do not meet with your approval, you may withdraw (as already mentioned, you may withdraw at any time).

If you have any concerns regarding this experiment, you may contact either Dr. R. C. Williges at 231-4602 or Dr. Ernest Stout, chairman of the Institutional Review Board for the Use of Human Subjects in Research, at 231-5281.

If you have any questions about the experiment or your rights as a participant, please do not hesitate to ask. The researcher will do his or her best to answer them, provided that the answer would not pre-bias the experimental results.

Your signature below indicates that you have read and understand your rights as a participant (as stated above), and that you consent to participate.

____

Participants Signature

____

Witness' Signature

Print name and address if you wish to receive a summary of the experimental results.

____

____

____

Appendix B. Detailed Task Instructions

INSTRUCTIONS

Your task is to drive the wheelchair or the simulator around the indicated course. The course layout will be the same for the actual wheelchair and the simulator. There are actually two versions of the simulator. One version displays the path from the perspective of sitting on the wheelchair. In this perspective, you can see your knees in the lower portion of the screen. The other version displays the path from the perspective of sitting two feet behind the simulator. From this perspective, you can see the position of the wheelchair on the path.

You can drive the wheelchair, both real and simulated, by manipulating the standard joystick. When driving the simulator, manipulation of the joystick causes the simulated path to move on the screen in a manner similar to the movement of an actual path relative to an actual wheelchair. The actual wheelchair will leave a colored line on the floor when it is driven so that information can be gather on wheelchair behavior.

Before the experiment begins, you must transfer into the control wheelchair provided by the experimenter. The experimenter and an assistant are there to help you make this transfer according to your instructions. There are six experimental tasks that you will be asked to participate in. Because the order of these tasks is different for each subject, the experimenter will tell you the order of the tasks before you begin. Two of the tasks will involve driving the wheelchair around the course laid out in tape. You will be required to wear a safety belt around your torso when driving the wheelchair. Before participating in these two tasks, you will then be given a chance to drive the wheelchair in the center of the room. In order to participate in the tasks, you must successfully navigate the wheelchair through a ten foot long, six foot wide course laid out in tape. After you have done this, and when you feel comfortable with the wheelchair, you may practice driving the wheelchair around the course for three minutes. One of the two tasks involving the actual wheelchair consists of driving the wheelchair in low speed around the course. The other involves driving the wheelchair in high speed around the course. You will be asked to drive two laps in each direction for both wheelchair tasks. Try to drive the wheelchair as fast as you can, while maintaining accuracy. Try to keep the rear wheels within the boundaries of the course. The course has been made narrow so that deviations outside of the course will occur. These deviations are expected and should not bother you.

The other four tasks involve the use of the simulator. The simulator tasks are to be completed in much the same way. You will be seated in front of the computer screen and given a chance to practice driving through the simulated courses. There are two simulator configurations, both of which have two speed settings. In one simulation configuration, you will see your knees at the bottom of the screen. You may use these to help keep you centered with respect to the path. In the other simulation configuration, you will see the course from the perspective of sitting two feet behind the wheelchair. You will be able to see the rear wheels of the wheelchair with respect to the course. Note that when driving the simulator, as you turn to the left, the path moves to the right with respect to the wheelchair. You may have to drive the simulator a little to get used to this effect. To get back to the path, you would move the joystick to the right. You may practice each task for three minutes. If you have any questions during the practice driving of the simulator, you may ask the experimenter. You will not be able to ask the experimenter any questions once the experimental task is under way.

Your objectives for driving the simulator will be the same as for driving the actual wheelchair. You will try to complete the course in as little time as possible, while maintaining accuracy. Try to drive so as to keep the rear wheels in the course. Again, it is not expected that you will be able to stay within the course. The course is narrow and deviation is normal. Do not let this bother you.

If you have any questions, please ask the experimenter now. The experimenter will summarize the instructions when you are ready.

Appendix C. Bipolar Rating Scales

Please answer all of the questions to the best of your ability. Read each scale carefully before responding. Place an "X" between the vertical divisions on the point of the scale, as in the example below.

Example

Easy |___|___|___|_X_|___|___|___| Difficult

How easy was the simulator to use on a straight section of path?

Easy |___|___|___|___|___|___|___| Difficult

How easy was the simulator to use on turns?

Difficult |___|___|___|___|___|___|___| Easy

How similar was the feel of driving the simulator to driving a power wheelchair on straight sections of path?

Similar |___|___|___|___|___|___|___| Not Similar

How similar was the feel of driving the simulator to driving a power wheelchair on turns?

Similar |___|___|___|___|___|___|___| Not Similar

How realistic was the display?

Not Realistic |___|___|___|___|___|___|___| Realistic

How realistic was the response of the simulator to your control inputs as compared to driving a power wheelchair on straight sections of path?

Not Realistic |___|___|___|___|___|___|___| Realistic

How realistic was the response of the simulator to your control inputs as compared to driving a power wheelchair on turns?

Realistic |___|___|___|___|___|___|___| Not Realistic

How useful would the simulator be in predicting wheelchair performance?

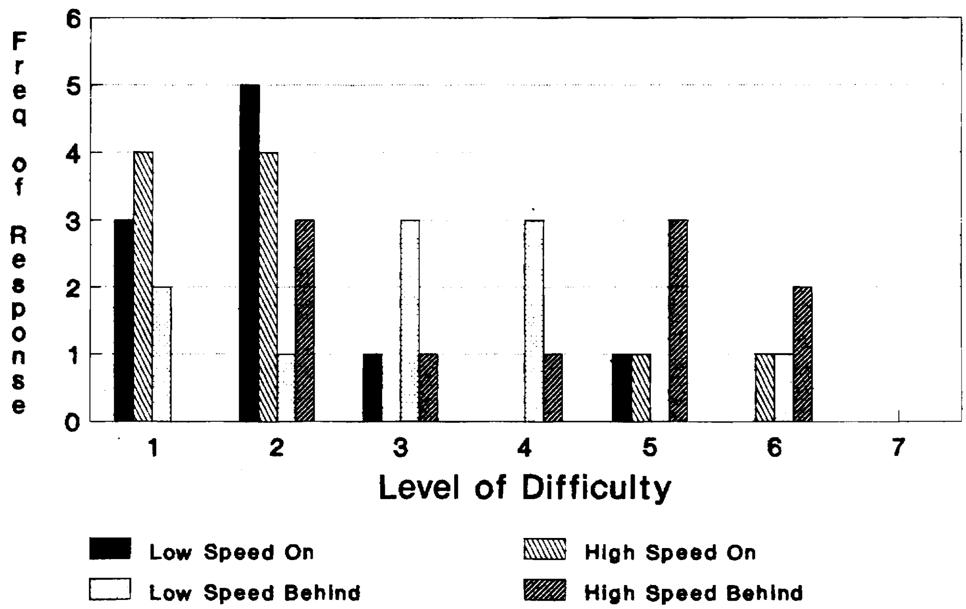
Useful |___|___|___|___|___|___|___| Not Useful

How accurately would the simulator predict power wheelchair performance?

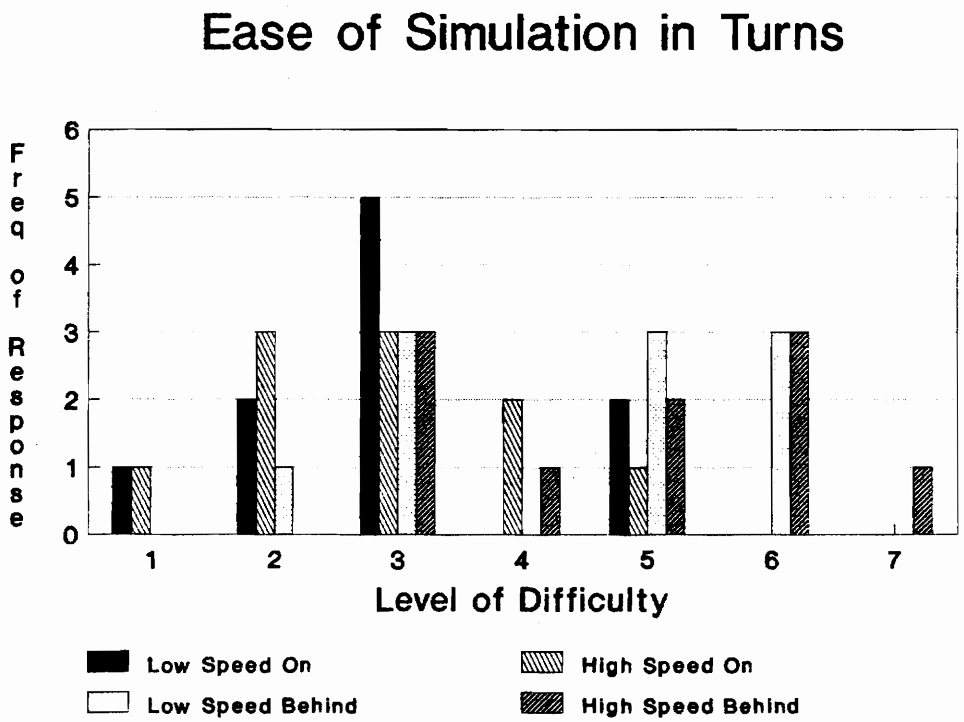
Not Accurate |___|___|___|___|___|___|___| Accurate

Appendix D. Results of Bipolar Rating Scales

Ease of Simulation in Straight Sections

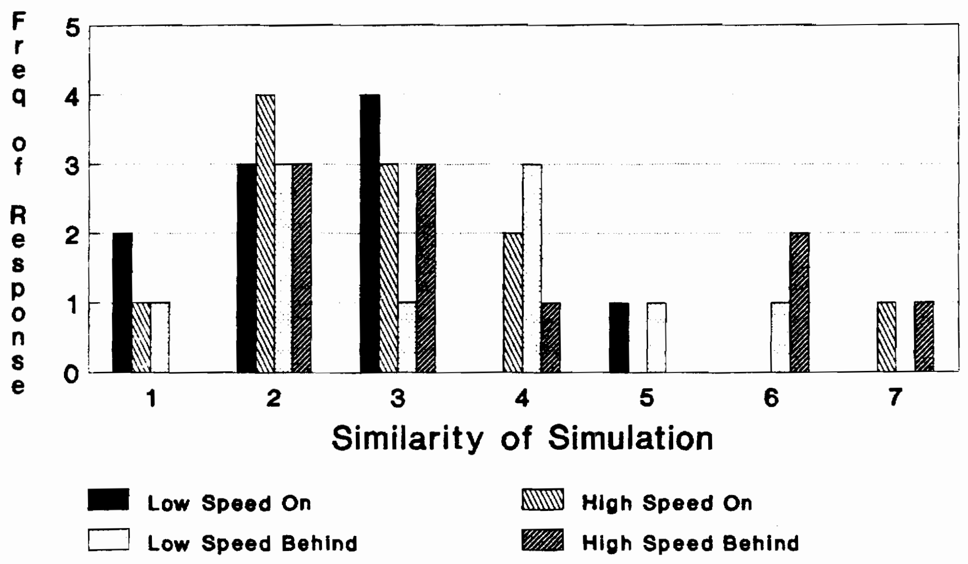


Note: Low numbers denote less difficulty

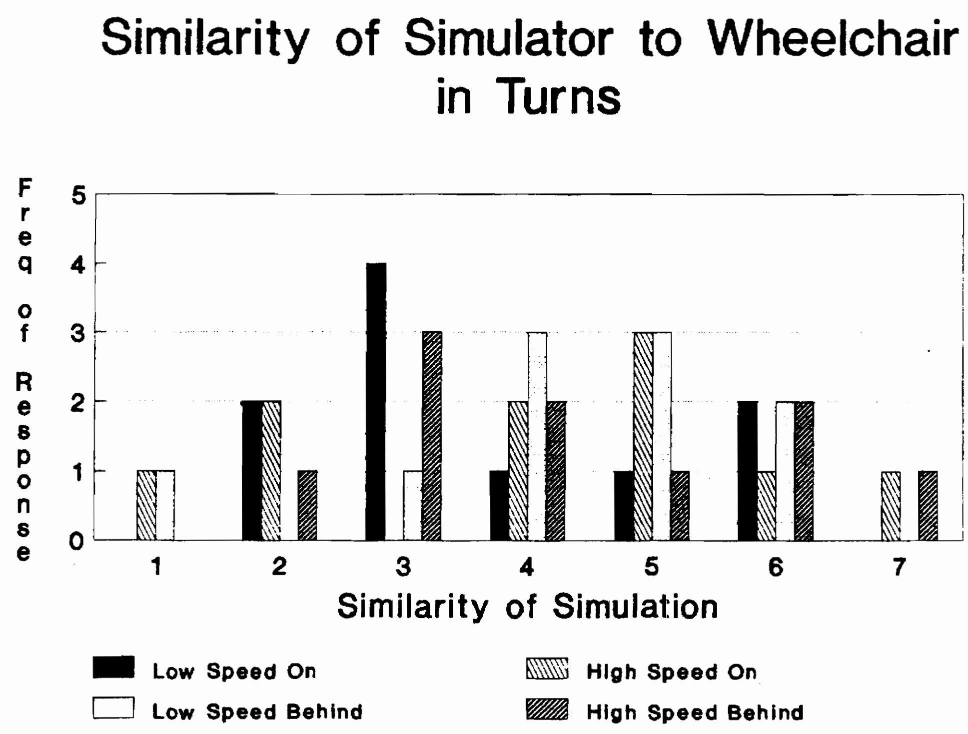


Note: Low numbers denote less difficulty

Simularity of Simulation to Wheelchair in Straight Sections

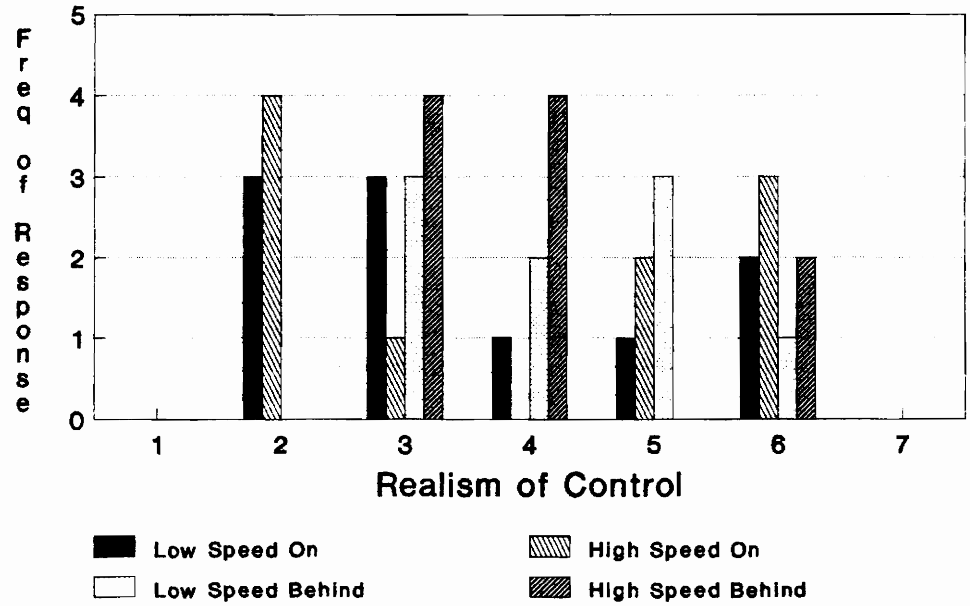


Note: Low numbers denote more similar

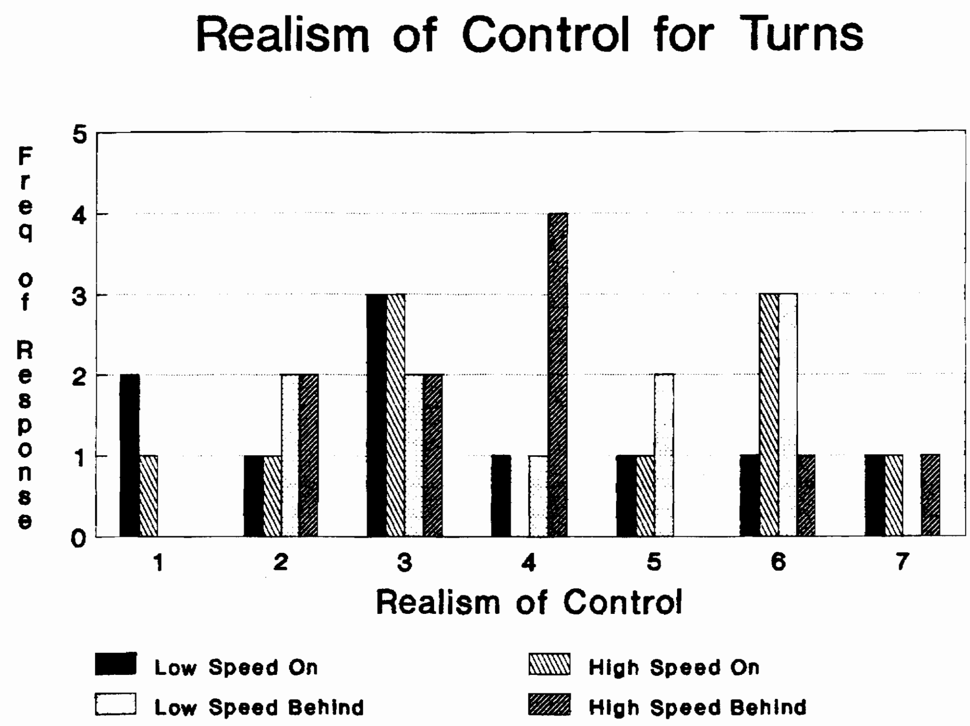


Note: Low numbers denote more similar

Realism of Control for Straight Sections

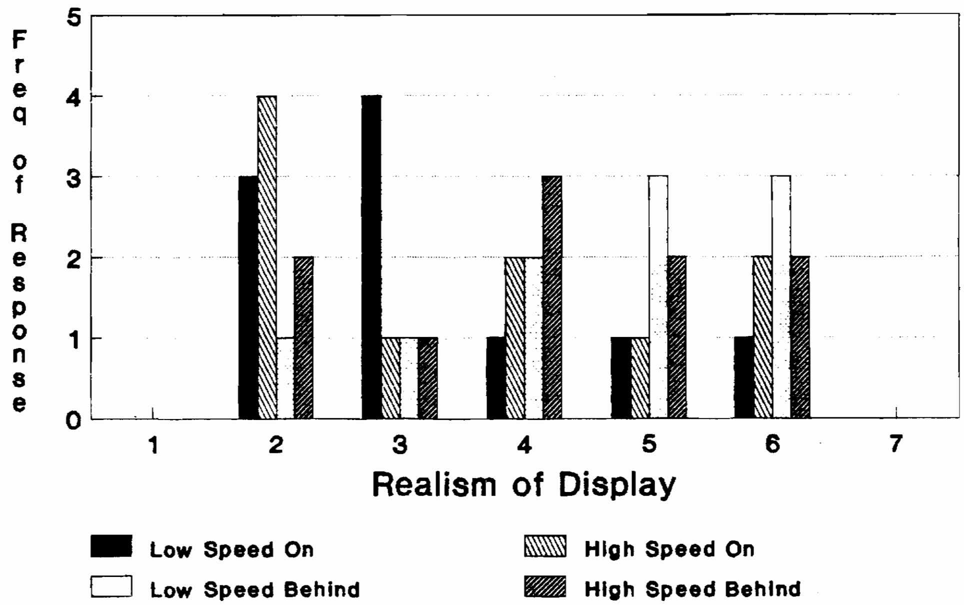


Note: Low numbers denote more real

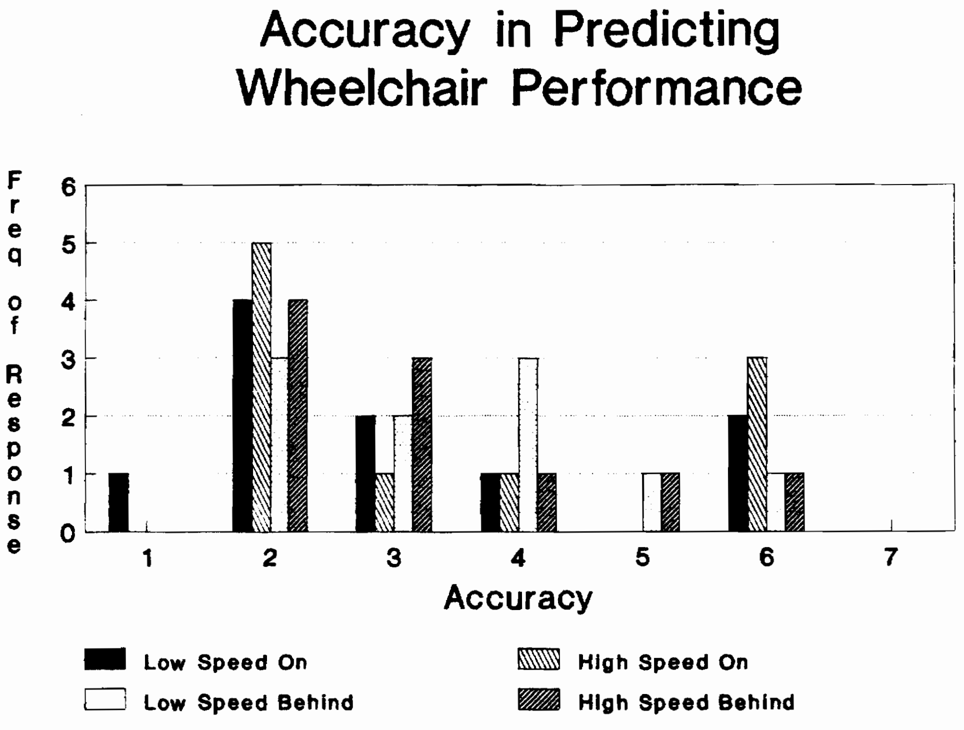


Note: Low numbers denote more real

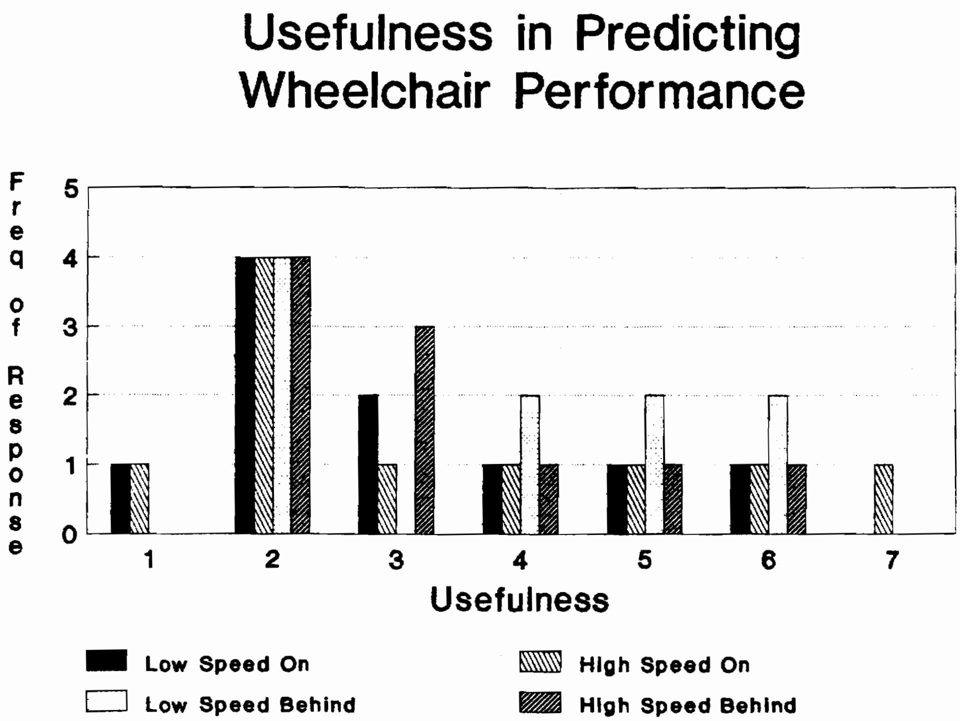
Realism of Display



Note: Low number denotes more real



Note: Low numbers denote more accuracy



Note: Low numbers denote more useful

Appendix E. Post-Test Questions

How different was the simulator from your power wheelchair?

1(N) "The control was very different. Turning wheelchair had more momentum in turning than the simulator."

2(N) "Not too much."

3(N) "The wheelchair had a jerkiness which affected how you moved while with the screen it was just hand/eye coordination."

4(N) "It didn't have momentum. Power off joystick caused the real wheelchair to continue to roll. Compensation was easier on the simulator. They were very different in feel, but similar in visual perspective."

5(D) "At low speeds they were similar. At high speeds the simulator was easier. The simulator was similar to my wheelchair at high and low speeds."

6(D) "Hard to say - Not all together different."

7(D) "A lot different - both perspectives."

8(D) "The behind view was real hard and a lot different. The other was right on track."

How was the simulator different from your power wheelchair?

1(N) (no answer)

2(N) "It was easier to go around turns in their simulator - easier to compensate for your mistakes."

3(N) (no answer)

4(N) "With viewing from rear, wheels seemed to straddle the lines. Straight sections were dotted on simulator and not on course. Seemed like speed was more controllable with the simulator."

5(D) "Didn't feel the force of gravity. You lose total vision on the simulator."

6(D) "It was harder to get back on course once off. Simulator was easier in that it didn't jerk you."

7(D) "It was a lot more responsive, a lot more delicate. More responsive in relation to joystick."

8(D) "The view from the rear was tough."

How could the simulator be improved so as to look more realistic?

1(N) "Hard to say. It was totally different to sit in front of a computer. The display looks good."

2(N) "Don't know. Eliminate flashing around turns."

3(N) "Show more of lower body, not just knees."

4(N) "The angles in turns didn't seem quite right. Like looking at a runway. Point perspective was wrong. Only portions of the track could be seen on the simulator, but there's an overview in real life."

5(D) "I Don't see purpose of two feel behind. Gave illusion of being higher."

6(D) "Looked fairly realistic. Get bugs out."

7(D) "More varied course. Lefts followed by rights. Couldn't tell from behind - knee position looked realistic."

8(D) "On - draw out actual wheelchair. Give more detail - almost complete."

How could the simulator control system be improved to respond more realistically?

1(N) "Add more momentum in turns."

2(N) "Don't know."

3(N) "Simulator was more fluid. Wheelchair was more jerky. Otherwise they were the same."

4(N) "Add momentum. Couldn't feel any angular momentum."

5(D) "It responded realistically. It was closer to a normal wheelchair than the control wheelchair."

6(D) "Simulator had slower reaction."

7(D) "Figure in factor of caster turning. On the simulators you could turn on a dime. In wheelchair you had to wait for it to turn."

8(D) "The actual wheelchair controls would take off quicker than the simulator. The wheelchair was jerkier. Rear view seemed more sensitive. Momentum pretty close."

Is the course layout used in this study representative of the paths you might follow in normal wheelchair operation? What might make it more realistic?

1(N) "Good enough. Enough turning points."

2(N) "Up and down grades maybe."

3(N) "Yes - typical turns. Add rough areas (grass vs. tile, over curves). Maybe go backwards. Maybe pulling up to a table."

4(N) "In normal operation, back up and down ramps. Up and turning. Down and turning."

5(D) "Larger course would be better. Need better wheelchair."

6(D) "Not realistic. No one goes in circles. More realistic to not make sharp turns. Wheelchair too wide in behind view."

7(D) "Curves instead of straightaways and corners. Small curves. Put rough spots (wood) in course to bounce wheelchair around."

8(D) "A maze might be more realistic. Go to a house plan. Back up from table, going in and out of various rooms."

Do you have any additional comments?

1(N) (no answer)

2(N) (no answer)

3(N) "Simulator was pretty good. Easier to move knees between lines in turn than the large back of a wheelchair. When you see knees in the simulator or wheelchair, you always assume back will follow. The back of wheelchair was hard to keep in lines."

4(N) "You should have asked if I had ever ridden a wheelchair before. Rode a manual wheelchair for a couple of weeks about 10 or 12 years ago."

5(D) "Made me dizzy. Especially at high speeds. Fortress Scientific can go nine mph."

6(D) (no answer)

7(D) "It was interesting."

8(D) (no answer)

1(N) (no answer)

Vita

Mr. A. Todd Lefkowicz received his B.S. in Industrial Engineering and Operations Research from VPI & SU in 1987. He has worked for four years as a rehabilitation engineer, practicing in the area of service delivery. He has performed internships as a rehabilitation engineer at the Cerebral Palsy Research Foundation in Wichita, KS, and the Woodrow Wilson Rehabilitation Center in Fishersville, VA.

Mr. Lefkowicz was employed for two years at the Center for the Disabled in Albany, NY. There he designed, fabricated, and implemented assistive devices in the areas of wheelchair mobility, augmentative communication, worksite modification, activities of daily living, and recreation. He also oversaw engineering students from Rensselear Polytechnic Institue as they worked on senior design projects to benefit the disabled.

Mr. Lefkowicz currently is employed by Sullivan Diagnostic Treatment Center in Harris, NY. There he develops assistive technology for the areas of special education, activities of daily living, and vocational and pre-vocational training. Mr. Lefkowicz also currently consults with the Wadsworth Center for Laboratories and Research in Albany, NY, where he is involved in the development of a brain-computer interface to enable people with severe disabilities to provide input to a computer through brain wave modulation.

A Todd Lefkowicz