DESIGN AND EVALUATION OF A DISTRIBUTED, SHARED CONTROL, NAVIGATION ASSISTANCE SYSTEM FOR POWER WHEELCHAIRS

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A significant number of individuals with disabilities is denied powered mobility because they lack the visual, motor, and/or cognitive skills required to safely operate a powered wheelchair. The Drive-Safe System (DSS) is an add-on, distributed, shared control navigation assistance system for powered wheelchairs, intended to provide safe and independent mobility to such individuals. The DSS is a human-machine system in which the user and machine share navigation control. The user is responsible for high-level control of the system, such as choosing the destination, path planning, and some navigation actions, while the DSS overrides unsafe maneuvers through autonomous collision avoidance, automatic wall following, and door crossing.

This dissertation reports the design and development of the DSS, followed by results from rigorous engineering and clinical evaluations. The engineering evaluations tested technical aspects of the DSS such as sensor coverage, maximum safe speed, maximum detection distance, and power consumption. Clinical evaluations included testing the DSS with Orientation & Mobility (O&M) specialists, ambulatory and non-ambulatory visually impaired individuals, and able-bodied controls. We compared the performance of the DSS with conventional navigation aids such as canes that are commonly used in conjunction with wheelchairs based on measures such as time for task completion and number of collisions. Additionally, we collected data with the NASA-TLX to gain insight into users' subjective experience with the DSS.

Results indicate that the DSS was able to provide a uniform and reliable sensor coverage field around the wheelchair and could successfully detect obstacles as small as 3 inches in height to overhanging obstacles at a height of 55 inches. The DSS significantly reduced the number of collisions compared to using a cane. Users rated the DSS favorably despite the fact they took longer to navigate the same obstacle course than they would using a cane. Visually impaired participants reported experiencing less physical demand, and had to exert less effort in order to achieve better performance when using the DSS, compared to using a cane. These findings suggest that the DSS can be a viable solution for powered mobility in populations with visual impairment.

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1.0 INTRODUCTION AND BACKGROUND

1.1 MOBILITY IMPAIRMENT

Muscular weakness and/or neurological dysfunction may prevent people from walking independently and, in some cases, force them to use wheelchairs and scooters for their mobility needs. Individuals with spinal cord injuries (SCI), multiple sclerosis (MS), traumatic brain injury (TBI), hemiplegia, cerebral palsy (CP), amyotrophic lateral sclerosis (ALS), spina bifida, arthritis, or lower limb amputations form the main user population for wheeled mobility equipment (WME) [1]. There are approximately 2.8 million WME users in the United States [1], of which10% use powered wheelchairs and over 80% use manual wheelchairs [1-4].

Much of the published literature has advocated the use of powered mobility for people with mobility impairments and limited physical strength [5-8]. In a large survey of powered wheelchair users [9] in which they were asked to describe their initial and long-term experiences, a large percentage reported that they felt empowered due to their increased ability to complete tasks. Powered wheelchairs offer the benefits of independent mobility while allowing individuals to devote their energy towards activities of daily living [10]. Several studies have shown that people of different age groups benefit from access to independent mobility [11-13]. Independent mobility is a key component in maintaining the physical and psychosocial health of an individual [11, 14, 15]. Further, independent mobility increases vocational and educational opportunities, reduces one’s dependence on caregivers and family members, and promotes feelings of self-reliance [11, 15].

Even though the benefits of the powered mobility are well documented, the safety issues associated with the operation of powered wheelchairs are the single most important factor that prevents most clinicians and rehab practitioners from prescribing powered mobility [16-18]. A survey of 55 practicing clinicians [16] revealed that

- 9–10% of their patients who receive powered wheelchair training find it extremely difficult or impossible to use the wheelchair for activities of daily living;
- 40% patients find it difficult or impossible to steer and maneuver a powered wheelchair;
- 27% of these clinicians reported seeing at least as many patients who cannot use a powered wheelchair as patients who can; and
- all the clinicians believed that nearly half of patients unable to control a powered wheelchair by conventional methods would benefit from a navigation assistance system.

1.2 VISUAL IMPAIRMENT

Legal blindness is defined as maximally corrected visual acuity of 20/200 or less in the better eye, or a total diameter of the visual field in that eye of 20” or less [19]. 5.3% of all WME users are either legally blind or have serious difficulty in seeing [1]. The American Federation for the Blind (AFB) has estimated that 9.61% of all individuals who are legally blind also use a wheelchair or scooter, in addition to another 5.25% of individuals who have serious difficulties seeing, but are not legally blind [5]. There are reports of visually impaired individuals using a white cane or guide dog along with a manual wheelchair, but this is not common practice [20].

Visual and physical impairments often accompany the natural aging process. Macular degeneration, cataracts, glaucoma, and diabetic retinopathy are the leading causes of visual impairments among older adults. According to the 2007 disability status report [21], 40.3% of non-institutionalized individuals age 75 and older in the US have conditions that substantially limit one or more basic physical activities such as walking, climbing stairs, reaching, lifting, or carrying. Further, 23.6% of individuals in this population have sensory disabilities, which include blindness or severe visual impairment. The American Federation for the Blind has predicted that the number of individuals age 65 or above who have severe functional limitations in vision will increase 284% from the year 2000 to the year 2050 [22]. The percentage of wheelchair users who are age 65 or above has steadily increased from 2.74% in 1990 to 5.2% in 2005. 12.28% of the non-institutionalized population age 85 and over uses wheelchairs, most of which are manual wheelchairs pushed by a caregiver or a family member [1].

Currently, the majority of non-ambulatory visually impaired individuals are seated in manual wheelchairs and pushed by other persons [20]. Being pushed by a caregiver creates a feeling of dependence, which can lead to a lack of motivation and learned helplessness [11, 23-25]. Reduction in functional mobility is linked with reduced participation and loss of social connections [14]. Psychologically, a decrease in mobility can lead to feelings of emotional loss, anxiety, depression, reduced self esteem, social isolation, stress, and fear of abandonment [15, 26].

There is limited literature addressing the use of powered wheelchairs by individuals with combined visual and mobility impairments. A case study of a visually impaired, powered wheelchair user who uses a white cane for navigation assistance was presented in [27]. Another case study of the use of a guide dog with a powered wheelchair by a visually impaired person is presented in [7]. Other authors [20, 28] have evaluated the merits and limitations of using a white cane with a wheelchair. Some researchers also advocate the use of power assisted manual wheelchairs for this population [5]. The process of training an individual with visual and mobility impairments to operate a wheelchair using a cane or guide dog is very time, labor, and resource intensive. It requires the active involvement and participation of family members, caregivers, orientation and mobility experts, occupational therapists, rehabilitation engineers, and primary care providers [7, 29]. Combined visual and mobility impairment will be encountered with increasing frequency because of the growing elderly population, and it is therefore important to have alternative assistive technology that offers independent mobility for such individuals

1.3 SMART WHEELCHAIRS

The use of smart wheelchairs has been researched since the early 1980's as a form of assistance for people who lack the visual, motor, or cognitive skills required to drive a powered wheelchair. A detailed discussion of the population of users who will benefit from smart wheelchairs was reviewed in [6]. In the following section, current research on smart wheelchairs is reviewed. Current smart wheelchair research projects range in their applications, capabilities and use of sensors but can be broadly classified into semi-autonomous, autonomous, and shared control.

The most basic form of smart wheelchair uses bumpers, infrared sensors, and sonar sensors for collision avoidance [5, 23, 30-34]. Such devices can be used only in controlled environments that limit the likelihood of sensor failure. Most of these smart wheelchairs lack sufficient sensor coverage, which poses a risk of severe collisions that could harm the user or cause damage to surrounding property.

Some smart wheelchairs achieve safer navigation by employing a laser rangefinder along with sonar and IR sensors for more reliable and comprehensive sensor coverage [35, 36]. Using a laser rangefinder can be of great help in drop-off detection, but the cost of the laser rangefinder and associated hardware is prohibitively high for a commercially viable smart wheelchair. Other smart wheelchairs employ stereo vision cameras for obstacle and drop-off detection and localization [37].

Some smart wheelchairs provide point to point navigation by following a colored lane, or a magnetic ferrite marker track or a barcode [34, 38-41]. Lane following technology can restrict the user’s motion to the guided lanes only and requires significant modifications to the living environment of the user. Once the wheelchair's user leaves the marked path, the technology of the assisted system is rendered useless.

Single switches, “sip and puff” devices, tongue operated joysticks, head operated joysticks, and chin operated joysticks are common in rehabilitation technology and have also been used in smart wheelchairs [12]. Current approaches involve various interface methods, such as touch-screen or voice recognition interfaces [42, 43]. Facial expressions and gesture recognition have also been used as input [44-46]. Others detect the user’s eye movements using eye trackers either to guide the wheelchair directly in the direction of gaze [44], or to select menu items on a display [34, 39, 41]. A detailed literature review of these smart wheelchairs was presented in [47].

Despite a long history of research in smart powered wheelchairs, very few smart wheelchairs are available commercially. The reason for this is that underlying cost of sensors and computing hardware that makes smart wheelchairs prohibitively expensive. Secondly, there have been no comprehensive engineering and clinical evaluations of these technologies and none of these technologies have been approved by the FDA, therefore most smart wheelchairs are sold for research purposes only. For example, two North American companies, Applied AI (TAO-7) and ActivMedia (Chariot), sell intelligent wheelchair bases for the development of autonomous wheelchairs for research purposes, but neither system is intended for use outside of a research lab [47].

The Wheelchair Pathfinder was a commercial product sold by Nurion Industries in early 2000 and later discontinued. The Pathfinder was an electronic mobility aid designed for use by individuals with mobility impairments, including those who are blind or have low vision or who have limited arm or head control [8]. The CALL Center smart powered wheelchair is sold in the United Kingdom (UK) and Europe by Smile Rehab, Ltd. (Berkshire, UK) includes bump sensors, sonar sensors and the ability to follow tape tracks on the floor [23].

1.4 THE DRIVE SAFE SMART WHEELCHAIR SYSTEM

We believe that a combination of robotics and wheelchair technology can address the issues related to the safety and training of powered mobility for individuals who are unable to use a powered wheelchair due to impaired visual, cognitive, and/or motor skills. In this research, we propose shared control architecture for a smart wheelchair. By shared control we mean that the smart wheelchair does not replace the abilities of the driver but, rather, complements the users' skills. Further, the cost of computing and sensing hardware is reduced by using the wheelchair operator's sensory and planning skills without compromising functioning and the safety of the user.

Our past research on the development and engineering evaluation of smart wheelchair technologies has shown promising results in terms of viability and applicability of shared control technology [48]. Previous smart wheelchair technology from our research group includes the NavChair [49], Hephaestus [33], SWCS [32], and SPAM [5]. The Drive Safe System (DSS) is the fifth generation of smart wheelchair technology that our research group has built. The DSS is modular, embedded, distributed, shared control architecture for providing navigation assistance to powered wheelchairs. The DSS is add-on architecture, compatible with the major wheelchair brands (e.g. Sunrise, Pride) in the US.

The DSS is a human machine system in which the user and machine share the navigation control. The user is responsible for the higher-level control of the system, such as choosing the destination, path planning, and some navigation actions, while the DSS overrides unsafe maneuvers through autonomous collision avoidance, automatic wall following, and door crossing. The DSS also provides additional assistance in form of auditory and visual feedback to the user. The user decides the speed and direction of travel with a joystick. In the presence of obstacles, the DSS's collision avoidance routines override these commands, if necessary, slowing the chair or stopping it completely.

1.5 SPECIFIC AIMS AND HYPOTHESIS

The purpose of this study was to determine if the DSS provides effective independent mobility to people with visual and mobility impairments. The following specific aims and hypotheses were tested in this dissertation.

Specific Aim 1. To evaluate the effectiveness of the DSS versus cane on a navigation task based on quantitative measures such as number of collisions and task completion time. Following hypotheses were associated with the specific aim 1:

Hypothesis Q1. People will have fewer collisions when using the DSS than when using a cane.

Hypothesis Q2. The average time of completion for a task will be greater when using the DSS in comparison to a cane.

Specific Aim 2. To evaluate the subjective workload associated with the use of the DSS on a navigation task and compare it with the subjective workload associated with the use of a cane on a similar navigation task. Following hypotheses were associated with the specific aim 2:

Hypothesis S1. Perceived physical demand in a given navigation task will be lower when using the DSS than when using a cane.

Hypothesis S2. Perceived mental demand will be higher when using the DSS than when using a cane.

Hypothesis S3. Frustration when using the DSS will be lower than when using a cane.

Hypothesis S4. Perceived effort when using the DSS will be lower than when using a cane.

Hypothesis S5. TWL when using the DSS will be lower than when using a cane.

Specific Aim 3. To evaluate the performance and robustness of the DSS based on the quantitative measures (e.g. number of collisions, task completion time, number of system resets required during the trials, errors in the architecture) and subjective measures (e.g. workload, users' recommendation, investigators observation of users' performance) and, based on the results, determine the changes required in the hardware (e.g., electronics and sensor housings, mountings), software (e.g., slow threshold, stop threshold) and user interface (e.g., auditory feedback, visual feedback).

1.6 ORGANIZATION OF THIS DISSERTATION

The purpose of this research was to design and evaluate a clinically and commercially viable smart wheelchair architecture, which may facilitate independent mobility to individuals with a broad spectrum of disabilities. The design and architecture of the DSS is described in chapter 2. Reliability and performance tests of the DSS are reported in the chapter 3. Chapter 4 presents the outcomes from the user trials of the DSS with able-bodied participants when driving forward and Chapter 5 presents outcomes of trials with the same participants driving backwards. Chapter 6 and Chapter 7 present the evaluation of the DSS with Orientation & Mobility (O&M) specialists and visually impaired participants respectively. Evaluation of the DSS with non-ambulatory visually impaired individuals is described in Chapter 8. Chapter 9 summarizes the findings from the various phases of this study, describes future research and suggests possible modifications to the DSS architecture for safer and more efficient operation. Appendices A through H include the obstacle courses, study questionnaires, data collection documents and individual sensor coverage fields.

2.0 DRIVE SAFE SYSTEM (DSS)

The Drive Safe System (DSS) is an embedded, distributed, modular, and shared control, navigation assistance architecture for powered wheelchairs (see Figure 2-1). The DSS architecture is compatible with powered wheelchairs manufactured by several companies (e.g. Sunrise, Pride) and supports a variety of proportional input methods.

The DSS can be used in areas that have been modified to (1) reduce the likelihood of sensor failure and (2) limit the consequences of sensor failure. We believe that an individual who is motivated to use the DSS will be willing to make simple modifications to the environment(s) in which the DSS will be used. These modifications include (1) eliminating or obstructing glass walls and doors, (2) moving valuable, breakable things to places where the wheelchair can not break them, (3) using baby gates or doors to block stairwells, and (4) widening doorways to at least 32 inches. The DSS can be used as a regular wheelchair in unmodified environments, but cannot be relied on as a smart wheelchair.

Figure 2-1: Wheelchair equipped with the DSS

2.1 THE DSS ARCHITECTURE

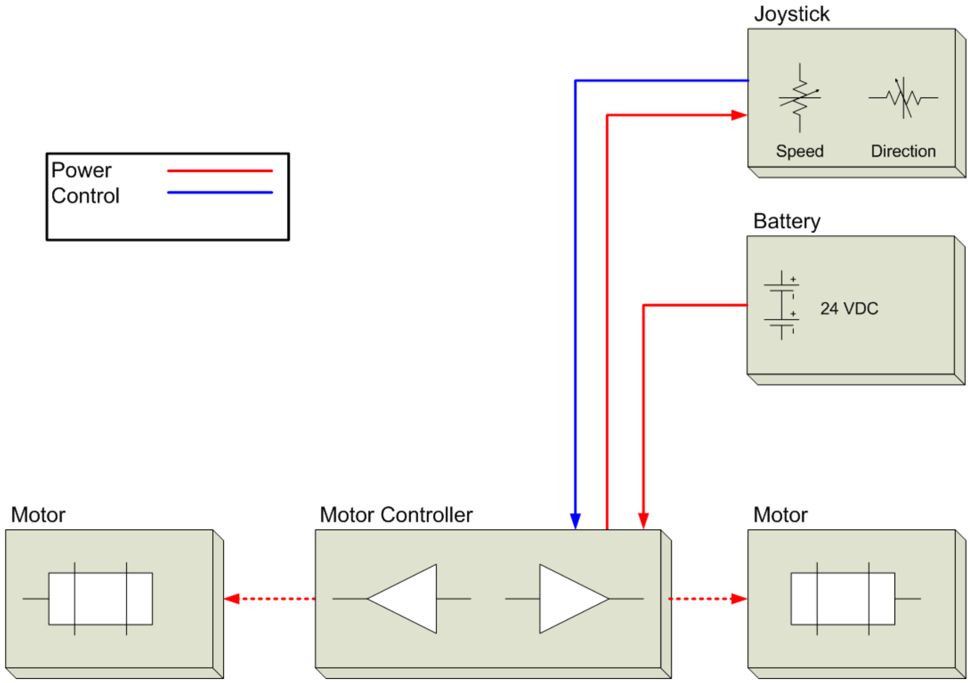

Figure 2-2: Functional Architecture of a Power Wheelchair

The main functional components of a powered wheelchair are the joystick, motor controller, batteries, and motors (see Figure 2-2). The DSS utilizes the underlying powered wheelchair's architecture for power and motor control (see Figure 2-3). The distributed architecture of the DSS supports a translator node and up to five sensor nodes (see Figure 2-3).

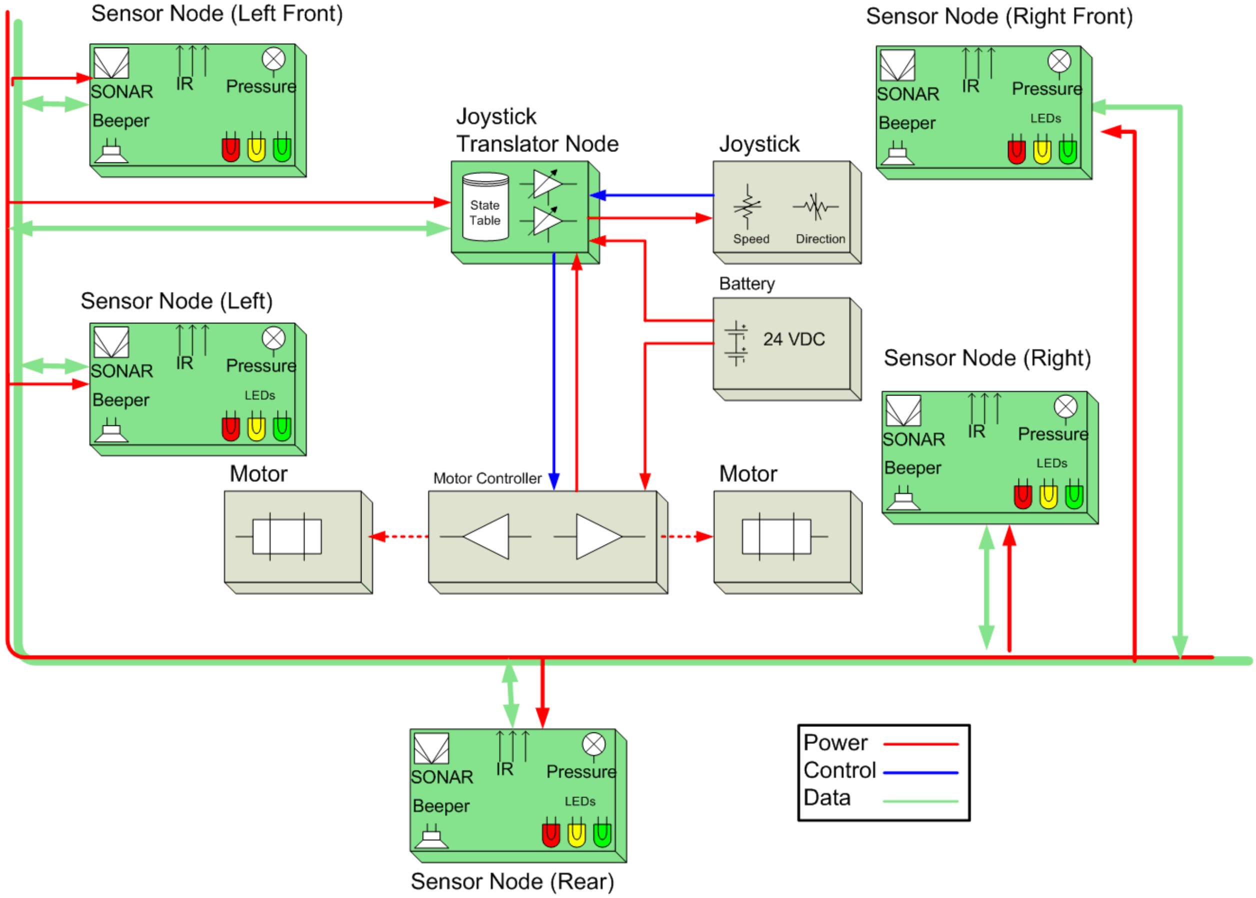

Figure 2-3: DSS Block Diagram

The life span of a powered wheelchair's varies from 3 to 5 years depending upon usage and driving conditions. The DSS's add-on architecture makes it useful across multiple wheelchairs, without requiring additional expenditure every time the user changes his or her wheelchair. Moreover, children with developmental disabilities can continue to use the DSS as their seating, positioning, and mobility needs change over time.

2.2 HARDWARE ARCHITECTURE

2.2.1 Sensor Node

The number of sensor nodes can vary from zero to five, depending upon the sensor coverage each user requires. People with limited neck motion might only require navigation assistance while backing up, so that only the rear sensor node is needed. Individuals with hemi-spatial neglect may require only coverage on the side of neglect, and will therefore only need either the left or right sensor node. As shown in Figure 2-4, each sensor node consists of up to five ultrasonic rangefinders (URs), five infrared rangefinders (IRs), two bumper inputs, two switch inputs, one beeper, and three status LEDs. Up to five sensor nodes are placed around the wheelchair, as shown in Figure 2-3, to provide complete sensor coverage around the wheelchair. The elements of a sensor node are placed in any of five types of sensor node shell (see Figure 2-4). Sensor node shells provide mounting, weather proofing, and safety to the sensor node hardware. The two front sensor node shells are mirror images of each other, one being mounted on front right and other on front left side of the wheelchair. Similarly, the two side sensor node shells are mirror images of each other and are mounted on the right side and the left side of the wheelchair. Finally, one rear sensor node is mounted on the back of the wheelchair.

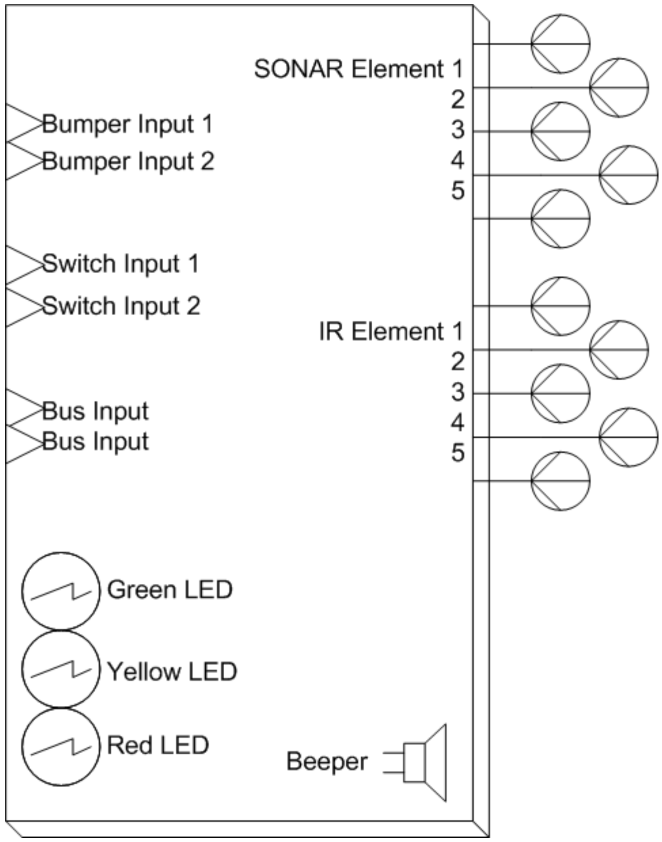

Figure 2-4: Sensor Node Block Diagram

Figure 2-5: Sensor Nodes and Translator Node

2.2.1.1 Ultrasonic Rangefinders

Each sensor node has five ultrasonic rangefinders (URs) operating at 42 KHz frequency. Four different URs are used in the current DSS architecture:

- LV-MaxSonar-EZ0,
- LV-MaxSonar-EZ1,
- LV-MaxSonar-EZ2, and
- LV-MaxSonar-EZ3.

The LV-MaxSonar-EZ[1] series of URs provides range information from 6 in (15.24 cm) to 254 inches (645.16 cm) with a 1 in (2.54 cm) resolution. Objects closer than 6 in (15.24 cm) produce a range of 6 in (15.24 cm). The MaxSonar-EZ0 has the largest detection cone while the MaxSonar-EZ3 has the smallest detection cone. URs with different sizes of cones were used to minimize cross talk and maximize coverage.

2.2.1.2 Infrared Rangefinders

Each sensor node has five infrared rangefinders (IRs) operating at 40 KHz modulation frequency. Two types of IRs are used in the current DSS architecture:

- Sharp IR-GP2Y0A02YK and
- Sharp IR-GP2D120.

The Sharp IR-GP2Y0A02YK provides range information from 8 in (20.32 cm) to 60 in (152.4 cm) with 1 in (2.54 cm) resolution. Objects from 0 to 8 in (20.32 cm) cannot be detected reliably because of the nonlinear behavior of these sensors in this range.

The Sharp IR-GP2D120 provides range information from 1.5 in (3.81 cm) to 12 in (30.48 cm) with 1 inch (2.54 cm) resolution. Objects from 0 to 1.5 in (3.81 cm) range cannot be detected reliably because of the nonlinear behavior of these sensors in this range.

2.2.1.3 Bumpers

Each sensor node has two interlink force sensing resistors[2] (FSRs) in ribbon form of up to 24 in (60.96 cm) in length and 0.5 in (1.27 cm) in width. FSRs are robust, polymer thick film

[1] MaxBotix Inc. Baxter, MN.

[2] Interlink Electronics, Inc. Camarillo, CA.

(PTF) devices that exhibit a decrease in resistance when increased pressure is applied to the surface of the sensor. Interlink FSRs have lifespan of 10 million cycles. There are 10 bumper segments in the DSS architecture, which cover the area around the wheelchair as shown in the Figure 2-6. When an obstacle touches a bumper segment the sensor node transmits the position of the obstacle to the translator node.

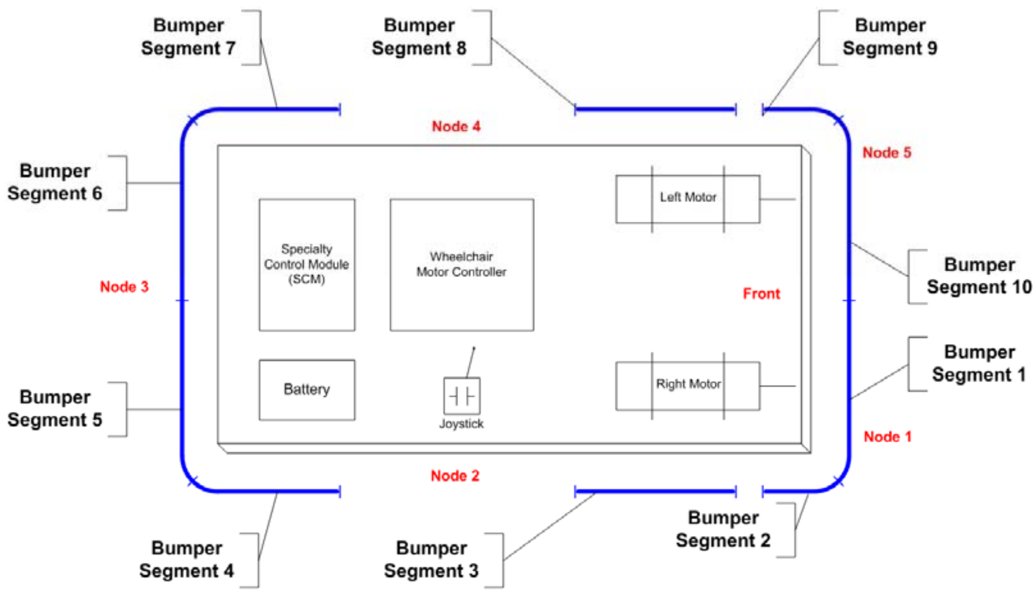

Figure 2-6: Bumper Block Diagram

2.2.1.4 Beeper and Light Emitting Diodes (LEDs)

Each sensor node has three status LEDs and a beeper. The LEDs (red, green, and yellow) and beeper are used to provide auditory and visual feedback to the user. There are programmed behaviors for the LEDs and beeper in each sensor node (e.g. showing the status of the sensor node, showing the position of an obstacle, showing when override mode is active, showing which bumper is pressed).

2.2.2 Translator Node

The translator node's function is to intercept the user's joystick signals and send the modified joystick signal to the wheelchair motor controller (See Figure 2-7). The translator node maintains the most recent state of each sensor node element (e.g. UR range information, IR range information, bumper state, LEDs status, switch status). This information is used to check for the presence of obstacles in the direction in which the user is intending to move. If the obstacle distance is below a pre-defined slow threshold the translator node will slow down the wheelchair. If this distance falls short of predefined stop threshold it will stop the wheelchair from moving any further towards the obstacle, thus preventing the user from hitting an obstacle. The translator node accepts analog, Controller Area Network (CAN), and serial input. The translator node also contains three LEDs which show the status of the translator node at any given moment.

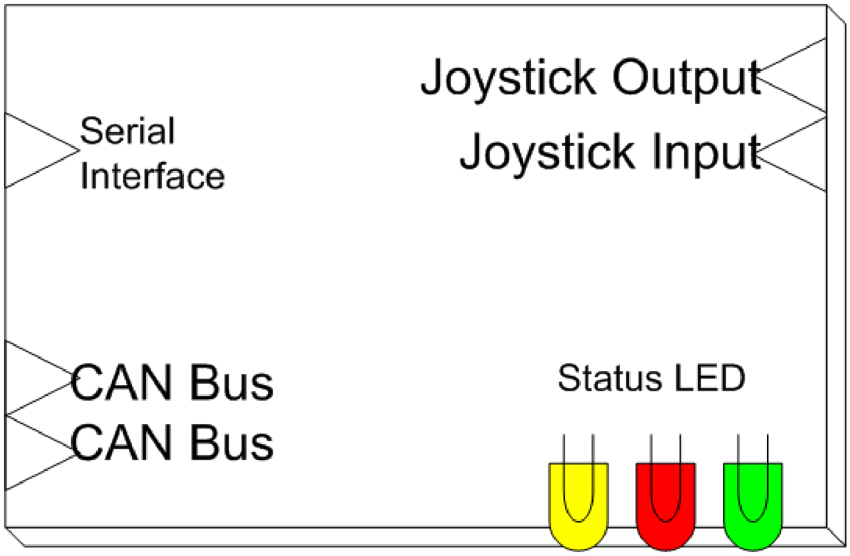

Figure 2-7: Translator Node Block Diagram

2.3 COMMUNICATION PROTOCOL

2.3.1 Controller Area Network

The DSS uses a Controller Area Network (CAN 2.0) for communication between nodes. The DSS CAN bus operates at 1 Megabits Per Second (MBPS) and uses 29-bit extended identifier messages for communication.

2.3.2 The Universal Synchronous Asynchronous Receiver Transmitter (USART)

Each node has a USART (serial) interface, which can be used for individual node debugging and programming. The serial bus in the DSS architecture operates at 115200 bits per second with no parity and one stop bit.

2.4 SOFTWARE ARCHITECTURE

The DSS software is distributed across the sensor nodes and the translator node. The translator node plays a central role in the implementation of the various behaviors of the DSS. These behaviors are implemented in various operating modes of the DSS, such as obstacle avoidance mode, door crossing mode, wall following mode, corridor crossing mode, and override mode.

2.4.1 Obstacle Avoidance Mode

The obstacle avoidance mode in the DSS uses range data from the sensors, state of the bumpers, and position of the joystick to provide safe navigation. Sensor nodes transmit range data from the URs and IRs to the translator node every 200 milliseconds. The bumper state is sent to the translator node whenever there is a change in state (pressed or not pressed). The area around the wheelchair is divided into 16 sectors as shown in Figure 2-8. Each of these sectors shows the possible direction of movement of the wheelchair and there is a direct correspondence between the angular position of the joystick and movement of the wheelchair in these sectors. For example, pushing the joystick from 67.5º to 90º will move the joystick in the direction of sector 1. URs and IRs provide sensor coverage around the wheelchair in each of these sectors. Every UR and IR sensor in the DSS architecture can provide coverage in one or more sectors around the wheelchair, based on its position and orientation. A detailed list of sensors and associated sectors is provided in Appendix F.

Sectors around the wheelchair are further categorized into three sections based on the position of the obstacles in these sectors:

Safe Region: The safe region is the region farthest away from the wheelchair. Having an obstacle in this region will not affect the movement of the wheelchair in this sector (see Figure 2-8).

Slow Region: The slow region is closer to the wheelchair than the safe region. An obstacle in the slow region in a given sector will reduce the speed of the wheelchair in that sector, but the direction of the movement will remain the same. The slowing down behavior is specific to each sector. The slowing function takes into account the minimum obstacle distance reported by the sensors in that sector and the speed of the wheelchair. The rate of slowing down is proportional to the speed of the wheelchair and the minimum obstacle distance.

Stop Region: The stop region is nearest to the wheelchair. An obstacle in this region in a given sector will stop the movement of the wheelchair in that sector. The stop threshold varies from sector to sector, and is larger in the front sectors (1,2,3,14,15,16) than in the rear sectors (8,9,10,11) because the forward speed is higher than the reverse speed and a larger stop threshold provides enough distance for the wheelchair to stop after signals are sent to the wheelchair controller.

The translator node gathers information from all the sensor nodes and organizes this range information in an obstacle density map (ODM) database. The translator samples the joystick at 20 Hz, and the joystick signal is converted into the corresponding sector number where the driver intends to move. Based on the intended direction of movement and obstacle density from the ODM in that sector, the translator can make three choices:

1. Do not change the input signals speed and direction signals, if there are no obstacles or obstacles are in safe region,
2. Slow down the wheelchair if obstacles are in slow down region, or
3. Stop the wheelchair if the obstacles are in stop region.

Whenever the translator stops the wheelchair because of an obstacle, users are notified through auditory and visual feedback.

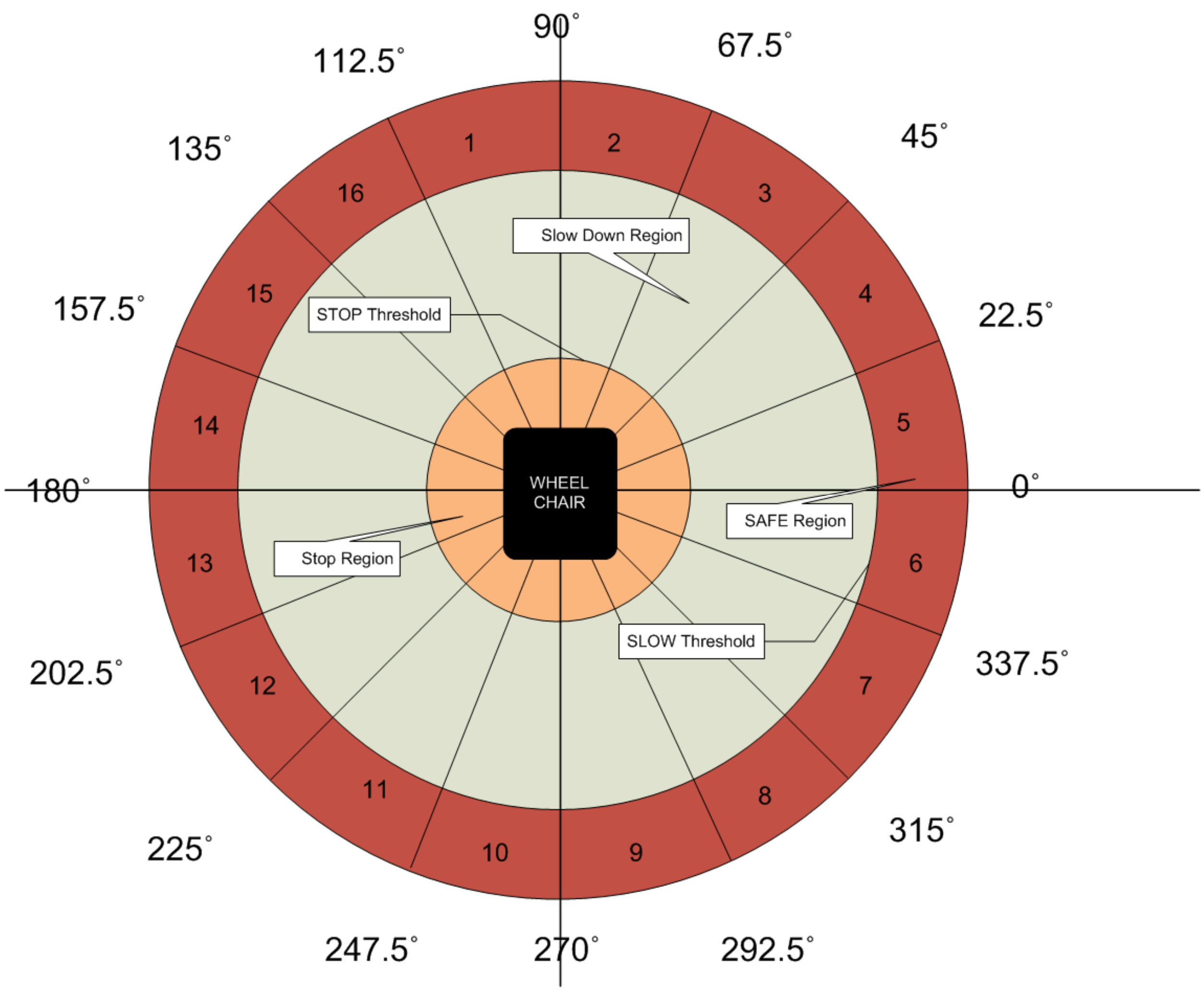

Figure 2-8: Wheelchair Sector Information

Short obstacles or obstacles with certain shapes and surface characteristics may not be detected by the URs and IRs. In those cases, the bumper modules provide extra safety by limiting the severity of collisions. There are ten bumper segments in the DSS architecture and each bumper segment covers specific sectors (see Figure 2-9). When a bumper segment is activated (pressed), the DSS will not allow movement in the sectors covered by the pressed bumper but will allow movement in direction of open sectors. Users are notified about bumper activation by auditory and visual feedback which is distinguishable from the feedback when the wheelchair is stopped by the proximity sensors.

Table 2-1: Bumpers Segments and their coverage in various sectors.

Sector	Bumpers
Sector 1	Segment 10, Segment 1
Sector 2	Segment 10, Segment 1
Sector 3	Segment 1, Segment 2
Sector 4	Segment 2, Segment 3
Sector 5	Segment 3
Sector 6	Segment 3
Sector 7	Segment 4
Sector 8	Segment 4, Segment 5
Sector 9	Segment 5, Segment 6
Sector 10	Segment 5, Segment 6
Sector 11	Segment 6, Segment 7
Sector 12	Segment 7
Sector 13	Segment 7
Sector 14	Segment 8
Sector 15	Segment 8, Segment 9
Sector 16	Segment 9, Segment 10

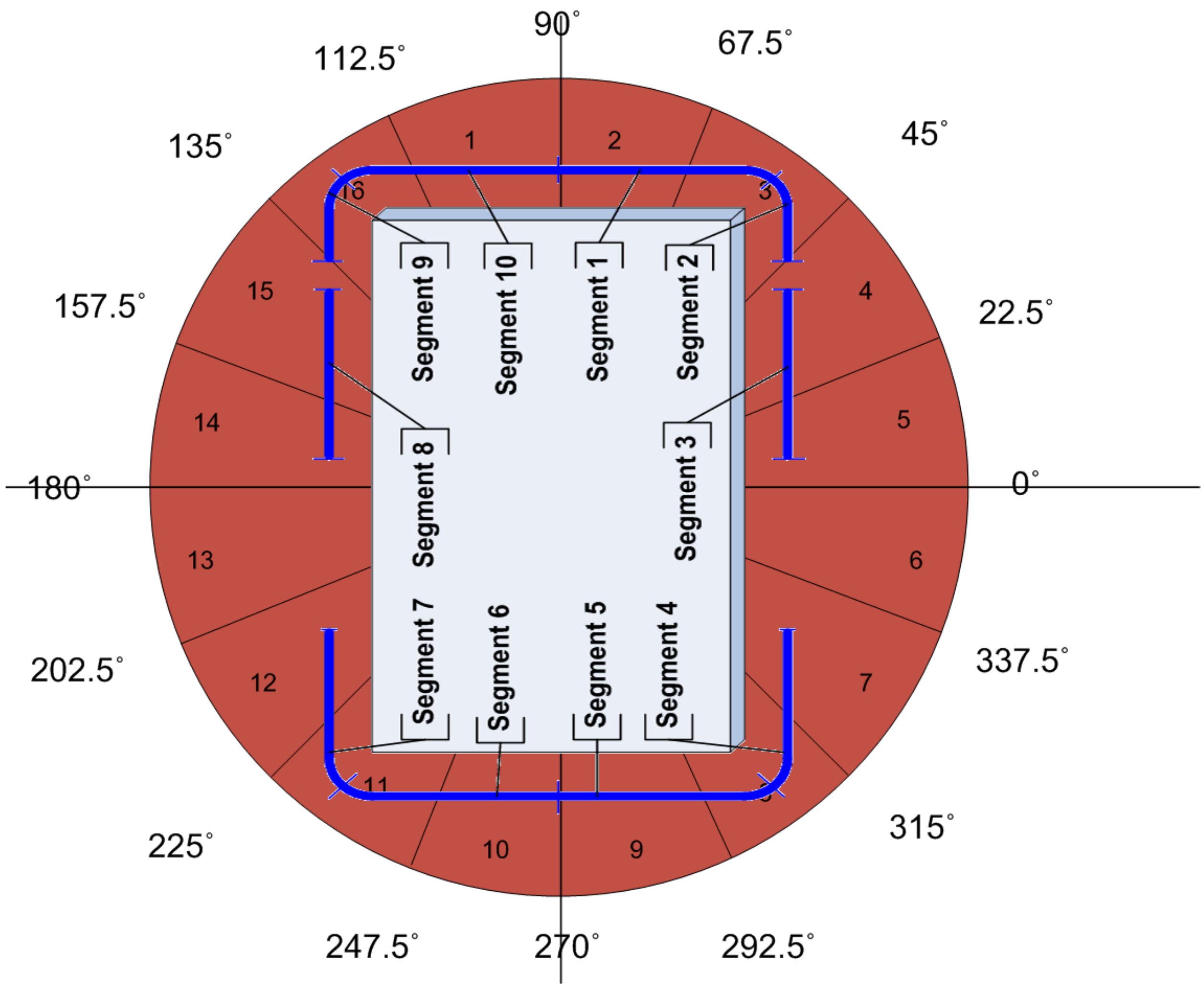

Figure 2-9: Bumpers covering sectors

2.4.2 Override Mode

The override mode reduces input signals to 35% of their value. In this mode, the DSS does not take range data from the proximity sensors into account, but keeps the bumpers active. Whenever a bumper touches an object, the translator stops the movement of the wheelchair in the sectors that bumper is covering. The override mode is useful in situations where the user needs to get close to something (e.g. desk, water fountain, light switch) but the DSS is stopping the wheelchair because of its obstacle avoidance mechanism. In situations like this, the user can press the override switch to go into the override mode and can get close to the object in question. Users are notified when the DSS is in override mode by a distinct sound pattern from one of the sensor nodes. When users are done using override mode, they can revert to the normal obstacle avoidance mode by pressing the override switch once again.

2.4.3 Door Passing Mode

Wheelchair users often need to pass through doorways to move from one area to another, but the obstacle avoidance mode of the DSS can make it difficult for drivers to pass through doorways because the narrow doors may be confused with the obstacles. The DSS architecture has a special mode called “Door Crossing” mode which facilitates passing through doorways without stopping the wheelchair while maintaining the safety of the user.

Door passing mode uses range data from the sectors listed in

Table **2-2**. The translator node creates an obstacle density map (ODM) in each sector around the wheelchair. Every time the translator node sends a control signal to the wheelchair, it checks if the ODM matches with the pattern defined for the doors in

Table **2-2**. If a pattern match is obtained for the front door, the translator checks the direction in which the driver is pushing the joystick. If the driver is pushing the joystick in the direction of sector 1 or 2, the translator node automatically triggers front door passing mode. When door passing mode is triggered, the wheelchair speed is reduced to 75% and the bumpers are kept active to avoid the severity of the collisions if they occur. Once door is passed, the DSS automatically changes the mode of operation to normal obstacle avoidance mode. Corridor passing mode in the DSS works on the similar principal as door passing mode because corridor is nothing but a longer doorway.

Table 2-2: Modes of Operations

	Stop threshold	Slow down Threshold	Safe Threshold	Movement Allowed
Left Wall Following Moving Forward mode	12, 13, 14, 15	11, 16	1,2,3,4	1,2
Left Wall Following Moving Reverse Mode	12, 13, 14, 15	11, 16	7,8,9,10	9,10
Right Wall Following Moving Forward	4,5,6,7	3,8	1, 2, 15,16	1, 2
Right Wall Following Moving Backward	4, 5, 6, 7	3, 8	9, 10,11,12	9,10
Corridor Mode Moving Forward	5, 6, 13, 14	4,7,11,15	1, 2, 3,16	1, 2
Corridor Mode Moving Backward	5, 6, 13, 14	4, 7, 11, 15	8, 9, 10, 11	9, 10
Front Door Crossing mode	4, 15	3,16	1,2	1,2
Rear Door Crossing Mode	7, 12	8,11	9,10	9,10

2.4.4 Wall Following Mode

Wall following mode facilitates driving in narrow spaces, so that the DSS will not stop the wheelchair by confusing narrow corridors with the obstacles. Wall following mode uses range data from the sectors listed in

Table **2-2**. Each time the translator node sends a control signal to the wheelchair, it checks if the ODM matches with the pattern defined for side walls. If a pattern match is obtained with the right side wall, the translator node checks the direction in which the driver is pushing the joystick. If the driver is pushing the joystick in the direction of sector 1 or sector 2, the translator node triggers the right side wall following mode and provides assistance in driving parallel to the wall while maintaining adequate speed, without getting stopped or becoming extremely slow because of the proximity to the walls. When the wall following mode is triggered, the wheelchair speed is reduced to 75% and the bumpers are kept activate.

3.0 PERFORMANCE AND RELIABILITY TESTING OF THE DSS

3.1 SENSOR COVERAGE

Sensor coverage can determine the DSS's ability to function safely and reliably. Sensors in the DSS architecture were positioned such that they would provide coverage and protection from very low height obstacles to the overhanging objects which might harm the user. The maximum height of an obstacle that the DSS can detect is 55 in (139.7 cm), while the lowest is 2.89 in (7.62 cm; see Figure 3-1and Figure 3-2).

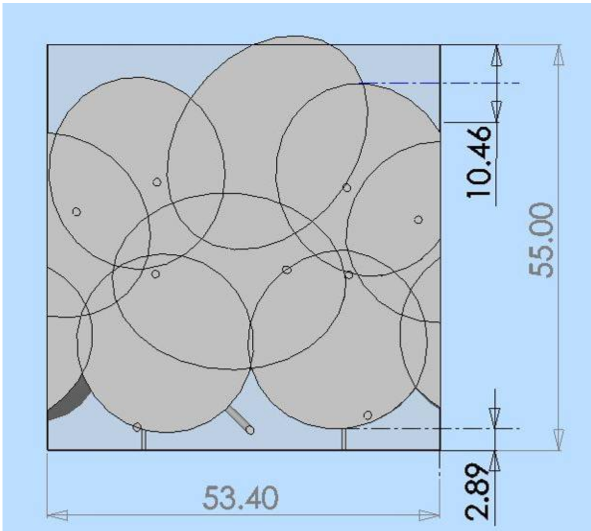

Figure 3-1: Front Sensor Coverage Field. The large circle represents coverage by an individual ultrasonic rangefinder sensor, while the small circles (dots) represent coverage by the individual IR sensor.

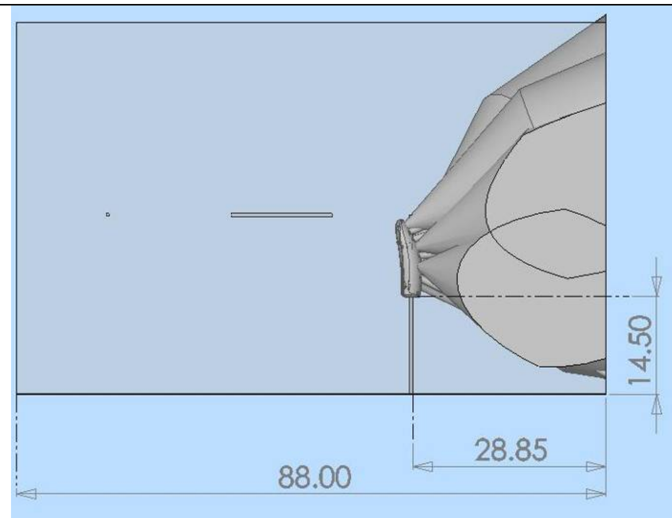

Figure 3-2: Maximum and Minimum Height Obstacle Detection

3.1.1 Sensor Coverage on a Sunrise Rhythm Power Wheelchair

The sensor coverage provided by the five sensor nodes was tested using a Sunrise Rhythm Power Wheelchair. The wheelchair was placed in the middle of an 8 ft x 8 ft (2.44m x 2.44m) grid. Each block in the grid was 2 in x 2 in (5.08cm x 5.08cm) for a total of 2304 squares. A 1 in (2.54cm) diameter by 60 in (1.52m) long rod was fixed vertically on a stable flat surface and used as an obstacle. Sensor coverage was determined by the ability of the sensors (URs and IRs) to detect this obstacle in the grid. The wheelchair covered an area of 54 in x 32 in (1.37m x .81m), so the obstacle was placed in each of the remaining 1872 squares in the grid.

To determine baseline sensor values, 20 samples of range data from each sensor were recorded without any obstacles in the grid. The means and the standard deviation (SD) of these twenty samples were calculated. These mean values were used as baselines for the obstacle detection ability of the sensors. The obstacle was then placed in all of the 1872 squares in the grid one at a time starting from the top left corner of the grid, and range data were recorded from all sensors.

Matlab[3] 8.0 was used for analysis of this data. For a given obstacle position in the grid, if any sensor range value was less than its baseline mean minus three SD, that grid position was considered covered by that sensor. Each grid cell could be covered by at least one UR, at least one IR, at least one UR and at least one IR, or no UR or IR.

Figure 3-3 shows the sensor coverage around the wheelchair. Areas in light blue are covered by at least one UR and at least one IR, dark blue by at least one UR (but no IRs), and yellow by at least one IR (but no URs). Areas in red are not covered by any UR or IR. Areas in the front of the wheelchair have coverage from both URs and IRs, but there are blind spots in the front right corner and rear corner of the wheelchair. Areas on the right and left sides of the wheelchair in red have no coverage from any sensors because the wheelchair cannot move in these directions.

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[3] The MathWorks, Inc., Natick, MA

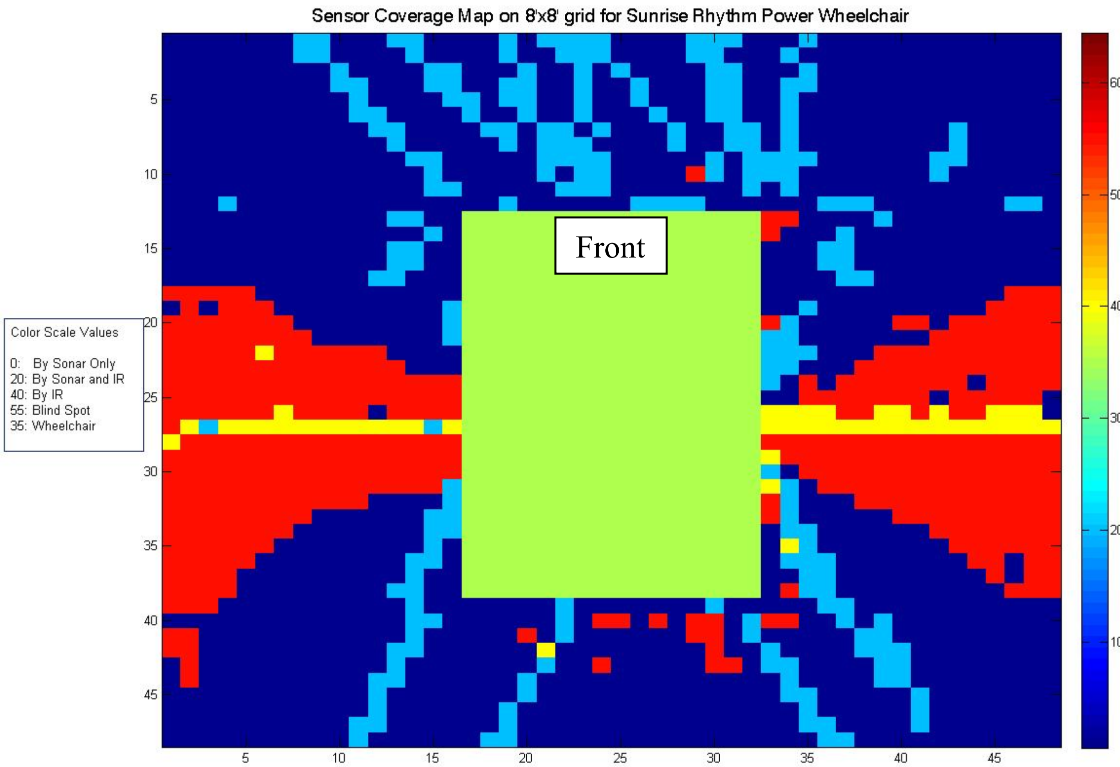

Figure 3-3: Sensor Coverage (both UR and IR)

Because of the size of the UR detection cone, some areas in the grid were covered by more than one UR. Figure 3-4 shows the number of URs covering each section in the grid. Areas in front of the wheelchair are very well covered, with some areas covered by as many as five URs. On the other hand, most of the area in the back of the wheelchair is covered by one or two URs and there are few blind spots on the rear right side of the wheelchair. We expect that, when the wheelchair is moving, obstacles will be detected before they enter a blind spot and possible collisions will be avoided. In addition, the size of most real world obstacles will be bigger than 1 in diameter and will be easier to detect.

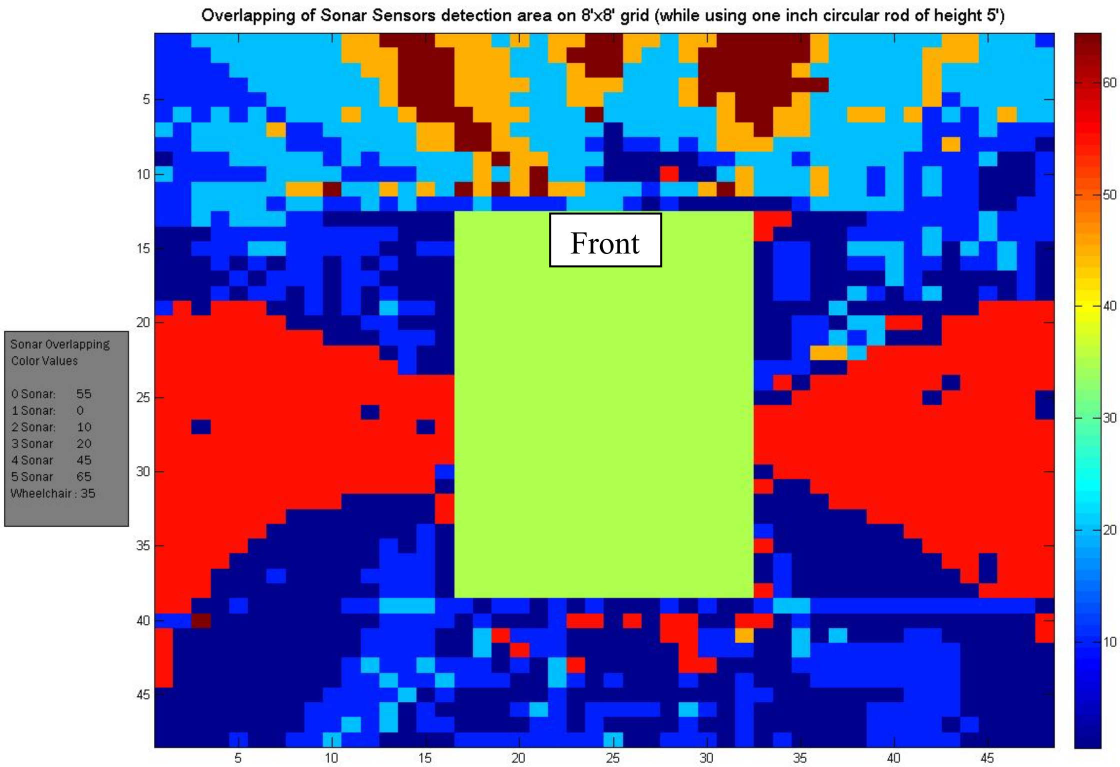

Figure 3-4: Number of URs Covering Each Grid Cell

3.1.2 Pride Mobility Q600 Power Wheelchair

Originally, there was no coverage in the middle of the right and left sides of the wheelchair (as shown in Figure 3-3) because the wheelchair is unable to move in those directions. However, initial testing and performance assessment with the DSS showed that having more coverage on the right and left sides of the wheelchair would help in doorways passing, corridor passing, and wall following modes. In the next phase of design, the sensor coverage field was modified, to increase coverage on the right and the left side of the wheelchair (see Figure 3-5). As shown in

Figure 3-5, there are blind spots and many very low coverage areas in the rear right corner of the wheelchair (shown in the red and yellow color dots). These blind spots are mainly due to the imperfections in the way URs are mounted in the rear sensor node shell, which is possibly a manufacturing defect. These blind spots can cause the collisions if obstacle is located in the rear right corner of the wheelchair. We expect that by changing the mounting in the rear sensor node we can eliminate all the blind spots in the rear right corner of the DSS.

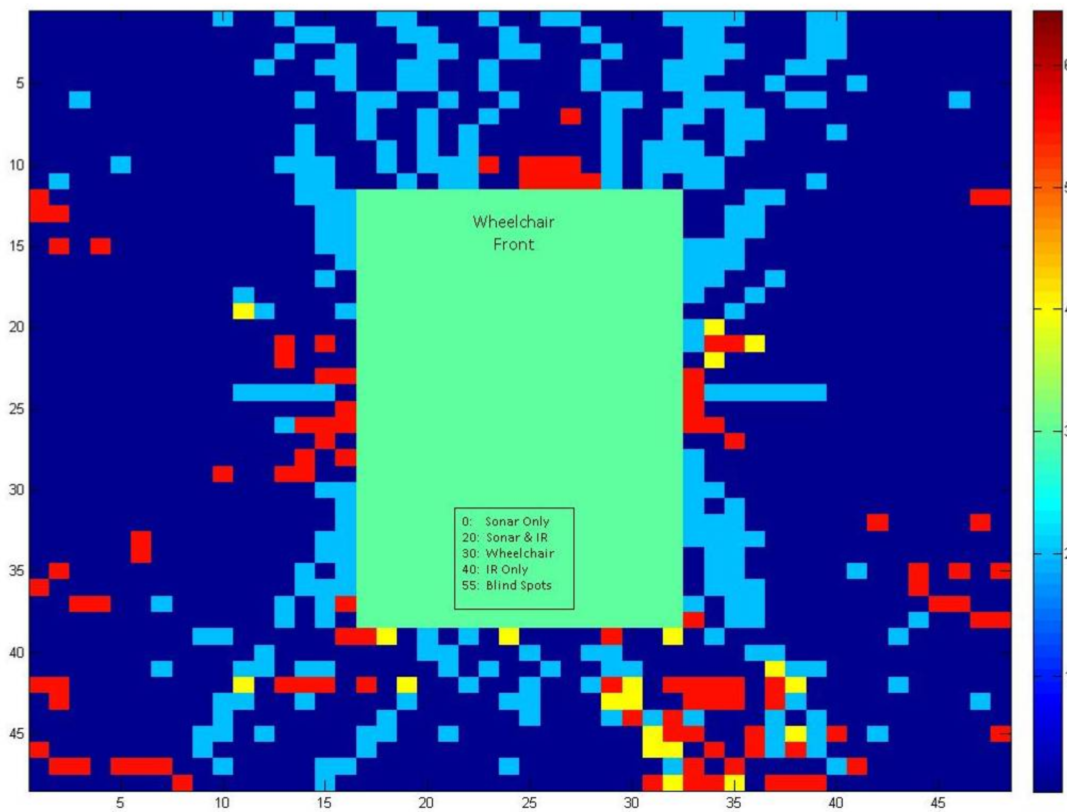

Figure 3-5: Modified Sensor Coverage

3.2 OBSTACLE DETECTION CAPABILITY

3.2.1 Maximum Obstacle Detection Distance

The MaxSonar-EZ0 (which has the largest detection cone of the URs on the DSS) and the Sharp GP2Y0A02YK (which has the greatest range of the IRs on the DSS) were used in these experiments. Cardboard tubes and wooden circular rods of various diameters were used as obstacles. An obstacle was placed 25 ft away from the front right sensor node of the DSS and then brought closer to the sensor node until it was detected. This procedure was performed for each size of obstacles mentioned in Table 3-1.

The maximum detection distance for each obstacle is shown in Table 3-1. The obstacle detection ability of the DSS varies with the diameter of the obstacle. Larger obstacles can be detected further away because of the URs. IRs could not detect obstacles that were smaller or further away because their range is small (less than 60 in; 1.52 m) and their detection cone is very small in comparison to URs.

The detection range of IRs and URs also depends upon the surface characteristics of the obstacles, ambient temperature, lighting, humidity, and air velocity [50]. The results in Table 3-1 were obtained indoors at a temperature of 71° F and fluorescent lighting. In real world situations, the detection range may be different than these results based on environmental factors, but the trend is expected to remain the same.

Table 3-1: Maximum Obstacle Detection Distance

Obstacle Diameter	UR (Inches)	IR (Inches)
1/8 in	62	No detection
1/2 in	81	12
1 in	97	37
2 in	106	43
3 in	116	49
6 in	133	52
8 in	160	52
12 in	211	52
24 in (wall)	246	58

3.2.2 Minimum Corridor Width

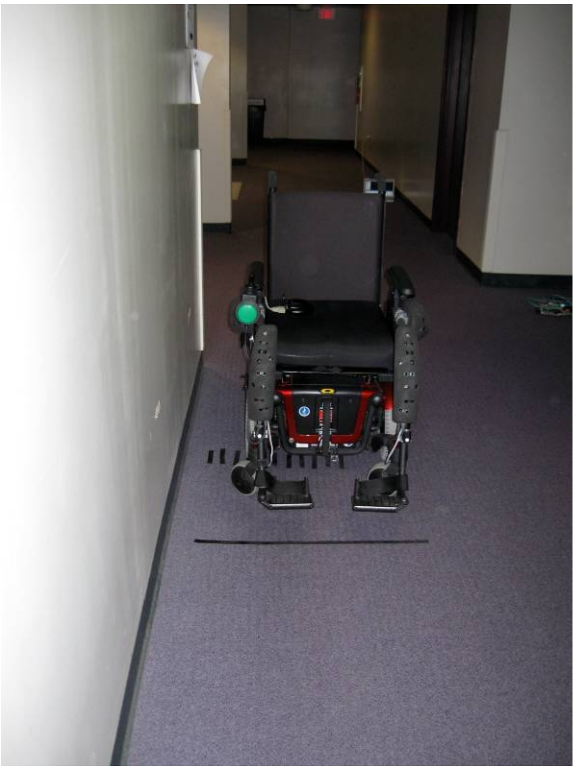

Figure 3-6: Experimental Setup for Wall Following

The DSS was placed parallel to a wall and driven 15 ft (4.57 m) while maintaining a constant distance from the wall. For each perpendicular distance five trials were administered. The number of times the DSS stopped the wheelchair from moving and the time of completion were noted. If the DSS stopped the wheelchair more than five times in a single trial, that distance was considered too short and not navigable with the DSS. The mean and SD of the time to complete the task and number of stops are shown in the Table 3-2. The DSS was automatically switched to the right wall following mode during this set of testing.

Results from these experiments indicate that the DSS was able to follow a wall as close as 6 in (15.24 cm) away without stopping. The DSS was unable to follow the wall when the distance was 4 in (10.16 cm) or less. This was due to the inability of the sensors to reliably report ranges less than 6 in (15.24 cm). Unreliable range values from the sensors would have resulted in a collision with the walls if the wheelchair had not been stopped by the translator node.

Table 3-2: Wall Following Test Results

Distance from the wall (in)	Time (sec)	Number of Stops
4	52.20 (±4.66)	3.80 (±0.84)
6	12.54 (±1.21)	0.60 (±0.55)
8	8.72 (±0.38)	0 (±0)
10	8.86 (±0.32)	0 (±0)
12	6.92 (±1.49)	0 (±0)
14	7.38 (±0.30)	0 (±0)
16	7.60 (±0.46)	0 (±0)
18	7.42 (±0.45)	0 (±0)
20	7.38 (±0.41)	0 (±0)
22	7.20 (±0.29)	0 (±0)
24	7.30 (±0.21)	0 (±0)

3.2.3 Minimum Door Width

Figure 3-7 Experimental Setup to Test Minimum Door Width Navigable by the DSS

3.2.3.1 Forward door crossing

The experimental setup for minimum door width travel is shown in the Figure 3-7. Two 18 in x 4 in x 48in (45.72 cm x 10.16 cm x 121.92 cm) foam sheets were used to simulate doors (see Figure 3-7). These two sheets were kept parallel in-line to each other and the distance between them was adjusted. The wheelchair began each trial 10 ft (3.05 m) away from the door opening. In each trial the wheelchair was driven towards the door until the rear bumper passed the rear edge of the foam sheets. Five trials were administered for each door width settings. The wheelchair was not allowed to go backwards and if the DSS stopped the wheelchair from passing through the doorway more than five times in a single trial, the trial was considered unsuccessful. As shown in Table 3-3**,** the wheelchair was consistently unable to cross doors narrower than 30 in (76.2 cm). The DSS was able to detect the doorways and automatically switched to the doorway passing mode during this set of testing as described in section 2.4.3. The DSS was unable to pass through the doorways of width 28 in (71.12 cm) or less. The DSS was able to cross the doorways width 32 in (81.28 cm) or more with 100 percent success rate.

There are several reasons why the DSS could not pass through narrow doorways:

1. The sensor nodes and bumpers increased the width of the wheelchair.
2. The minimum detection distance for the URs and IRs was too large; the smallest range value a UR will return is 6 in (15.24 cm), so it is difficult to know for certain whether an obstacle is 6 in (15.24 cm) away or 1 in (2.54 cm) away. Similarly, the non linear behavior of the IRs at short distances means they cannot determine range reliably at distances less than 8 in (20.32 cm).

3. The position of the sensors in the DSS architecture was not appropriate for detecting doors and narrow openings. The large detection cone of the URs made it difficult to find the exact location of an opening.

Table 3-3: Door Crossing Test Results

Door width (inches)	Rate of successful attempts (%) (Moving Forward)	Rate of successful attempts (%) (Moving Backwards)
28	0	0
30	80	0
32	100	0
34	100	0
36	100	0
38	100	20
40	100	40
42	100	80
44	100	100
46	100	100
48	100	100

3.2.3.2 Backwards door crossing

Tests were performed to evaluate the underlying wheelchairs ability to cross the doorways with the DSS active and moving backwards. Same experimental setup and protocol as described in the forward door crossing section 3.2.3.1 was used in these experiments too. Results from these tests have shown is Table 3-3. As shown in Table 3-3, the wheelchair was consistently unable to cross doorways width 36 in (91.44 cm) or less. The DSS was reliably able to cross the doorways 44 inches or more, with 100 percent success rate.

The DSS was consistently unable to cross the narrower doors (36 inches or less) when moving backwards, because the positions of the URs and IRs looking backwards in the right side, left side, and rear sensor nodes were not appropriate to detect the doorways and trigger the door crossing mode as described in section 2.4.3. Further, the large detection area of the URs detected the door posts as obstacles, even when they were not in the direction of movement of the wheelchair.

3.2.4 Maximum Safe Speed

The wheelchair was placed 10 ft (3.05 m) away from an obstacle formed by two 18 in x 4 in x 48in (45.72 cm x 10.16 cm x 121.92 cm) foam sheets (see Figure 3-8). The DSS was running in normal obstacle avoidance mode during this set of testing. The wheelchair was driven at full speed towards the obstacles until the DSS stopped the wheelchair from moving forward. When the wheelchair was stopped, the minimum distance between the obstacle and the wheelchair's footrests was measured. Ten trials were administered for each speed. The mean and SD of stopping distance and time of completion for each speed are shown in Table 3-4. The ideal required stopping distance was set at 4 in (10.16 cm) from the footrests, to accommodate the front bumpers. Speed at which the stopping distance was less than 4 in (10.16 cm) considered not a safe speed.

Figure 3-8: Experimental Setup for Maximum Safe Speed Tests

The results indicate that the maximum safe speed for the current sensor sampling rate and obstacle avoidance algorithm is 2.6 mph (116.23 cm/sec). The maximum safe speed of the wheelchair can be further increased by sampling the sensors more often and further modifying the obstacle avoidance algorithm to slow the wheelchair more rapidly in presence of obstacles at faster wheelchair speeds.

Table 3-4: Results from Safe Speed Tests

Speed (MPH)	Time	Stopping Distance
0.8	13.89(±0.49)	16.80(±0.40)
1.0	12.75(±0.38)	16.40(±0.52)
1.2	10.48(±0.53)	16.00(±1.05)
1.4	8.12(±0.83)	15.80(±1.03)
1.6	5.99(±0.34)	15.20(±1.03)
1.8	5.46(±0.43)	15.10(±0.99)
2.0	5.14(±0.45)	12.40(±0.97)
2.2	5.01(±0.52)	10.60(±0.97)
2.4	4.97(±0.78)	8.50(±1.65)
2.6	4.64(±0.59)	4.10(±0.57)
2.8	4.43(±0.60)	1.45(±1.29)

3.2.5 Bumper Sensitivity

A digital weight measuring scale was used to determine the amount of force required to activate the bumpers. The force on the bumper segments was applied to an area of 0.75 in x 1.50 in (1.90 cm x 3.81 cm). The force divided by the area was used to calculate pressure in the units of Pounds per Square Inch (PSI). For each bumper segment, ten data points of activation pressure were calculated. The mean and SD for each bumper segment are shown in Table 3-5.

The results indicate that bumper activation pressure is not uniform across the segments. Bumper segment five required the lowest activation pressure (M = 1.17, SD = 0.03), and bumper segment nine required the highest activation pressure (*M* = 2.74, *SD* = 0.04). The variation in activation pressure was due to variations in the tuning of the comparator circuit in the sensor node hardware. This tuning cannot be adjusted beyond a certain point because this may produce false positive activation of the bumpers.

Table 3-5: Activation Pressure for Bumper Segments

Bumper Segment	Force	Range	Pressure	Range
Segment 1	776.4(±38.60)	[708, 836]	1.52(±0.08)	[1.39, 1.64]
Segment 2	1012(±38.62)	[928, 1054]	1.98(±0.08)	[1.82, 2.06]
Segment 3	804(±25.91)	[760, 838]	1.57(±0.05)	[1.49, 1.64]
Segment 4	1126.8(±21.15)	[1088, 1166]	2.21(±0.04)	[2.13, 2.28]
Segment 5	599(±14.12)	[580, 620]	1.17(±0.03)	[1.14, 1.21]
Segment 6	776.8(±13.44)	[762, 804]	1.52(±0.03)	[1.49, 1.57]
Segment 7	1244(±36.64)	[1190, 1308]	2.44(±0.07)	[2.33, 2.56]
Segment 8	959.4(±25.94)	[910, 994]	1.88(±0.05)	[1.78, 1.95]
Segment 9	1398.6(±20.61)	[1366, 1430]	2.74(±0.04)	[2.67, 2.80]
Segment 10	1240.4(±31.08)	[1192, 1284]	2.43(±0.06)	[2.33, 2.51]

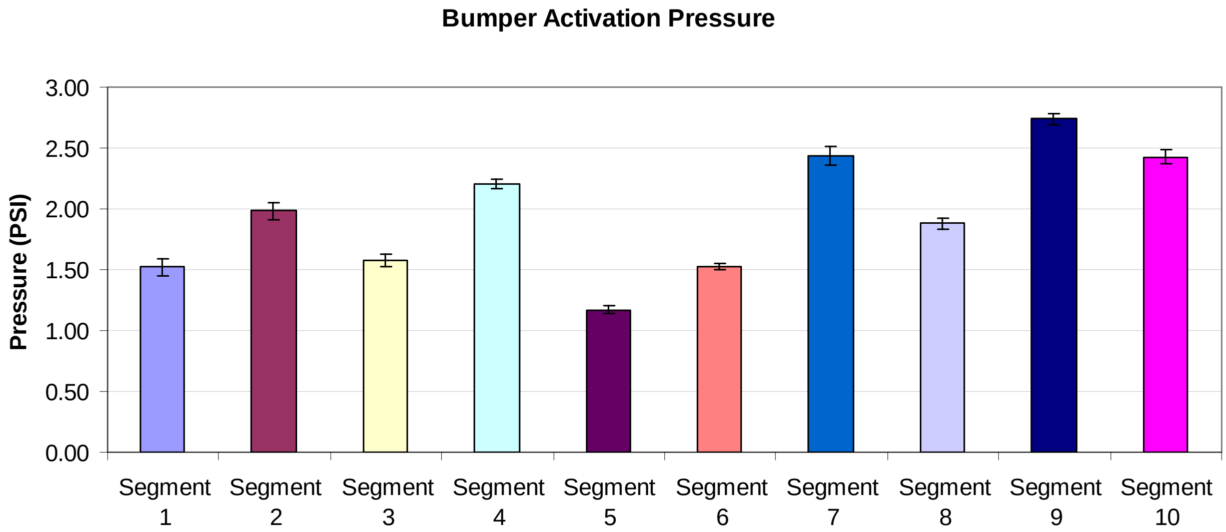

Figure 3-9: Bumper Activation Pressure

3.2.6 Power Consumption

The DSS architecture draws power from the underlying powered wheelchair batteries. The DSS hardware can operate anywhere between 12 and 35 volts. Since the DSS hardware will always be active when a person is using his or her wheelchair, the excessive power consumption by the DSS hardware can limit the performance and range of the underlying wheelchair. To reduce consumption of power there are two power states in the DSS: awake and asleep. The power consumption by the DSS is high when awake and low when asleep.

To test power consumption, a bench top power supply was used to supply 24 volts to the DSS hardware and current was measured using a digital multimeter. The average power consumption by the DSS hardware was 16.35 watts when the DSS was awake and functioning. Maximum power consumption (26.15 watts) occurred when all the sensors were ranging and all the LEDs and Beepers in the DSS architecture are switched on. Minimum power consumption occurred when the DSS was in sleep mode. When the DSS was asleep, the power consumption was 0.96 watt. The power draw of each component of the DSS is shown in Table 3-6.

The Pride wheelchair uses two gel-cell lead-acid batteries, with a 12V and 60 Amp-Hour rating. When drawing maximum current, the DSS architecture will reduce the available battery Amp-Hour by approximately 3%. A powered wheelchair travels 23.6 to 57.7km in a single charge [51], when equipped with the DSS this wheelchair will travel 22.9 to 56km. Use of the DSS with the wheelchair will not effect the battery life or number of charges required per day.

Table 3-6: Power Consumption by the DSS Architecture

Node	Minimum (watts)	Average (watts)	Maximum (watts)
Sensor Node	0.24	1.68	3.84
Translator Node	0.12	0.96	1.92
Whole DSS	0.96	16.35	26.15

3.2.7 Wheelchair Dimensions

Powered wheelchairs are designed to be narrow enough to fit most of the doors in home, work and community settings and short enough that the user will be able to turn the wheelchair in narrow spaces, such as in bathrooms, kitchens or public transportation, without hitting objects. The DSS requires additional hardware to be mounted on the underlying wheelchair. This hardware includes five sensor nodes, the translator node, ten bumper segments, wiring, and mounting and clamping hardware. The addition of the DSS hardware is expected to increase the dimensions of the underlying wheelchair, because the bumpers will alter the length and width of the wheelchair and the side sensor nodes will increase the effective width of the wheelchair, thus making it difficult to drive through doorways or narrow corridors. Table 3-7 shows the dimensions of a wheelchair equipped with the DSS system.

Table 3-7: Wheelchair Dimensions with the DSS

Increase / Hardware	Length (in)	Width (in)
Wheelchair	44	25.5
With bumpers	50	26.5
Sensor node	44	28
Whole DSS	50	28

Adding bumpers increased the wheelchair's length by 4 in (10.16 cm) in front of the wheelchair and 1 in (2.54 cm) in the rear of the wheelchair. The sensor nodes added no length to the wheelchair, but did add 1.75 in (4.45 cm) to each side of the wheelchair. The added width is likely to interfere with use of the wheelchair in areas with narrow doorways or tight spaces. By changing the mounting position of the side sensor nodes, it may be possible to reduce the width without compromising the functional effectiveness of the DSS.

The bumpers increased the length of the underlying wheelchair, particularly in the front of the wheelchair. This added length was 4 inches from the footrests. When a person sits on a wheelchair the effective length of the wheelchair is increased because the person's project out over the footrests. When comparing the added length due to bumpers with the effective length of the wheelchair with a shoe size of 10 (US Male), the additional length due to the bumpers was only 1 in (2.54 cm).

4.0 STUDY 1: ABLE BODIED SUBJECTS (FORWARD DRIVING)

4.1 INTRODUCTION

The study described in this section employed able-bodied individuals wearing blindfolds to simulate complete blindness. Using able-bodied subjects made it possible to recruit a large number of homogeneous participants, which facilitated group statistical analyses. However, the able-bodied participants were not experienced wheelchair users and did not have the orientation and mobility skills of people with visual impairments.

4.2 HYPOTHESES AND SPECIFIC AIMS

The purpose of this study was to determine if the DSS provides effective independent mobility to able bodied individuals when they are simulating the condition of people with visual and mobility impairments.

Specific Aim 1. Evaluate the effectiveness of the DSS versus cane on a forward moving navigation task based on quantitative measures such as number of collisions and task completion time. Following hypotheses were associated with the specific aim 1:

Hypothesis Q1. People will have fewer collisions when using the DSS than when using a cane.

Hypothesis Q2. The average time of completion for a task will be greater when using the DSS in comparison to a cane.

Specific Aim 2. Evaluate the subjective workload associated with the use of the DSS on a forward moving navigation task and compare it with the subjective workload associated with the use of a cane on the similar navigation task. Following hypotheses were associated with the specific aim 2:

Hypothesis S1. Perceived physical demand in a given navigation task will be lower when using the DSS than when using a cane.

Hypothesis S2. Perceived mental demand will be higher when using the DSS than when using a cane.

Hypothesis S3. Frustration when using the DSS will be lower than when using a cane.

Hypothesis S4. Perceived effort when using the DSS will be lower than when using a cane.

Hypothesis S5. TWL when using the DSS will be lower than when using a cane.

Specific Aim 3. Evaluate the performance and robustness of the DSS based on the objective measures (e.g. number of collisions, task completion time, number of system resets required during the trials, errors in the architecture) and subjective measures (e.g. workload, users' recommendation, investigators observation of users' performance) and, based on the results, determine the changes required in the hardware (e.g., electronics and sensor housings, mountings), software (e.g., slow threshold, stop threshold) and user interface (e.g., auditory feedback, visual feedback).

4.3 SUBJECTS

4.3.1 Recruitment

The study protocol was approved by the Institutional Review Board (IRB) of the University of Pittsburgh on March 10, 2008. A further modification in the study protocol was accepted by the IRB on September 3, 2008, after which the recruitment process was begun. Undergraduate and graduate students from University of Pittsburgh were recruited through IRB approved fliers posted in Forbes Tower at University of Pittsburgh.

4.3.2 Inclusion / Exclusion

Inclusion criteria for participants were as follows:

- Be older than 21 years of age
- Be able to read, write and understand instructions in English.
- Have normal hearing ability
- Be available to finish the trials in one or two sessions within a week

Exclusion criteria for participants were as follows:

- Do not have any medical condition that would interfere with driving a wheelchair while blindfolded, such as nausea or dizziness.

4.3.3 Demographics

19 participants (13 Males, 6 Females) were recruited for this study. Mean age of participants was 28.36 years (SD 3.91 y). Three participants had prior experience with power wheelchair driving but none was a regular wheelchair user.

4.4 PROTOCOL

4.4.1 Instrumentation

A Quantum-600[4] mid-wheel drive powered wheelchair (see Figure 4-1) was used for this study. The seat width was 18 inches with no tilt, no recline and no seat elevation functions. The Quantum 600 was controlled by a proportional joystick. The maximum forward speed of the wheelchair was set to 1.7 miles/hour and the maximum reverse speed was set to 1.3 miles/hour to match the average driving speed for wheelchair users [51]

The Quantum 600 was equipped with the Drive Safe System (DSS) and an emergency stop switch which could bring the wheelchair to immediate stop. A second switch enabled the experimenter to activate and deactivate the navigation assistance.

[4] Pride Mobility Products; Exeter, PA

Figure 4-1: Quantum 600 Electric wheelchair with Drive Safe System

A Sony boom box or a MacBook Pro laptop were used as sound sources to provide an auditory navigation target to participants. Participants were given the choice of the sound target to choose from such as songs, music, news, and talk shows, these sound targets were played on the boom box or laptop. The sound source was kept at 9.00 meter distance away from the start location of the trial and kept at height of 1.00 meter from the ground. An area of 3.30 x 7.50 sq. meters was used for the user trial. Safety glasses covered with paper tape on all the sides (front and side) were used as a blindfold to cover the front and peripheral vision. Cardboard cylindrical tubes 8 in (20 cm) diameter and 60 in (152.4 cm) tall were used as obstacles and wooden benches 36 in (91.44 cm) height were used to mark the boundary of the area used for the trials. Participants used a 48 in (121.92 cm) tall white cane to scan for obstacles in the environment.

4.4.2 Methods

4.4.2.1 Informed Consent

Prior to participating in the study, each participant read the Informed Consent Form. Once each participant indicated that the form had been read and understood, and agreed to participate, the informed consent form was signed. A copy of the informed consent form was given to the participants upon completion of the experiment.

4.4.2.2 Seating and Positioning

Depending upon participants' requirements, the seating and positioning of the wheelchair was adjusted by the investigator. For example, the wheelchair joystick was mounted on the right or the left side of the wheelchair, depending upon whether the participant was left-handed or right-handed.

4.4.2.3 Training

Once participants were comfortable with their seating and the positioning of the joystick, they were introduced to the wheelchair controller and the joystick interface. The experimenter explained the functioning of the wheelchair, the maneuvering of the wheelchair using a proportional joystick, and controller parameters such as maximum forward speed, maximum reverse speed, acceleration, and deceleration.

Participants were required to demonstrate verbal understanding of the system before they were given training on how to maneuver the wheelchair using the joystick. Participants' wheelchair driving skills were tested on two courses (see Appendix A .1) designed to enhance participants' familiarity with the wheelchair's dynamics and ability to maneuver in tight spaces without a blindfold. Participant traversed these courses while driving forward and then driving backwards until the participant was able to traverse the courses without hitting any obstacles. While driving on the test course, participants did not have support from the DSS proximity sensors but the bumpers were active; if a participant hit an obstacle the bumpers would stop the wheelchair.

Next, participants learned to drive the wheelchair with a cane while blindfolded. Participants were given instructions on how to use the cane to scan the environment and detect obstacles while moving forward and while moving backwards. Participants used their dominant hand to maneuver the joystick and their non-dominant hand to scan the environment with the cane. Participants were asked to complete two obstacle courses to practice navigation, while blindfolded and using a cane on a wheelchair.

Once participants felt comfortable and confident with using the cane, they received training on operating the wheelchair with the DSS. Participants received an explanation about the DSS architecture, its various behaviors and the logic the DSS uses to avoid collisions. Participants received an explanation about the auditory feedback patterns generated by the DSS. Part of the training, participants were blindfolded and asked to localize the position of the obstacles based on the auditory feedback from the DSS. When participants demonstrated that they understood the DSS and its operation, they were asked to approach obstacles placed in front of the wheelchair to observe the wheelchair's response to obstacles. Participants were then asked to approach obstacles placed to the side and rear of the wheelchair to observe the DSS's response in these situations. Participants were then blindfolded and asked to complete two obstacle courses using assistance from the DSS. Investigators observed the performance of the participants and instructed them on various navigation skills to use the assistance from the DSS effectively. These training courses gave participants an understanding of the obstacle distance thresholds of the DSS in various directions around the wheelchair. Number of training sessions with the DSS varied from 2 to 6, depending upon the participants' level of comfort and confidence in using the DSS.

The last set of training activities involved the use of cane and the DSS together. Participants were instructed to use the cane to determine the location of obstacles when the DSS stopped the wheelchair. Participants were instructed to hold the cane on their lap or in a position where it did not interfere with the sonar and infrared sensors when it was not being used. Participants were asked to complete two training obstacle courses in this condition to familiarize themselves with the use of cane with the DSS. Number of training sessions with the cane along with the DSS varied from 2 to 6, depending upon the participants' level of comfort and confidence in using the cane and the DSS together.

Table 4-1: Experimental Conditions

Condition	Blindfold	Cane	DSS	Bumper	Movement	No. of obstacles
Cane	Yes	Yes	No	Active	Forward	9
DSS	Yes	No	Yes	Active	Forward	9
Cane&DSS	Yes	Yes	Yes	Active	Forward	9

4.4.2.4 Experimental Design

Participants completed three trials under each of three experimental conditions (Table 4-1)

- Cane: Participant used a 48” cane for navigation assistance while driving the powered wheelchair.
- DSS: Participant used the DSS for navigation assistance.
- Cane&DSS: Participant used both the cane and the DSS for navigation assistance. Participants received feedback about the environment from DSS. Once stopped by the DSS, participants could use the cane to find the position of obstacles.

In each trial, participants were blindfolded and asked to reach a goal indicated by a sound source. Participants were asked to choose the type of sound cues they preferred (e.g. music, news, talk show). Order of experimental conditions (Cane, DSS, and Cane&DSS) and order of three obstacle courses (see Appendix A.2.1) in each condition were randomized. In each set of trial the obstacle course was assigned randomly to eliminate any learning of the obstacle course (see Appendix A.2.1). Participants were given four minutes to complete each trial. All trials were videotaped.

Participants were positioned at the start of the each trial as shown in Appendix A.2. One investigator carried a data collection sheet (shown in Appendix B) and filled in the sheet with observations during each trial. The other investigator walked behind the wheelchair and could bring the wheelchair to an immediate halt if a risk of danger to the participant was perceived.

If participants displaced an obstacle from its location, the obstacle remained in the displaced location until the end of the trial. If a participant knocked over an obstacle, investigators removed the obstacle from the wheelchair's immediate path of travel. Once both footrests of the wheelchair crossed the finish line participants were told to bring the wheelchair to a stop. The participant remained blindfolded while being moved back to the starting position for the next trial and the obstacle course was changed. After finishing the three trials in each condition, participants completed the NASA-TLX questionnaire shown in Appendix C.

4.4.2.5 Data collection

Task Completion Time (TCT): TCT was the time taken by a participant to navigate the obstacle course from the starting position to the finish line, measured in seconds.

Number of Collisions per Trial (NCT): A collision was defined as contact between the wheelchair and a cardboard tube or boundary wall. NCT shows total number of collisions for a user in each experimental condition (Cane, DSS, and Cane&DSS). In this study there were three trials in each condition, so NCT was total number of collisions in three trials together for each participant. The intensity and severity of a collision was determined based on the displacement of an obstacle from its initial position (see Figure 4-2):

1. Type I collision: When a cardboard tube was displaced by less than two inches (see Figure 4-3) or the wheelchair touched the surrounding wall without displacing the wall and without activating the bumpers. These collisions are unlikely to harm the user or environment because the wheelchair's speed is low and the participants retain control of the wheelchair.
2. Type II collision: When a cardboard tube was displaced by two to fourteen inches (see Figure 4-4) or the wheelchair displaced the surrounding wall without activating the bumpers. These collisions may harm the environment but are unlikely to harm the user or the wheelchair.

3. Type III collision: When a cardboard tube was displaced by more than fourteen inches (see Figure 4-5) or fell over, or the wheelchair displaced a surrounding wall. Type III collisions may harm the user, the wheelchair or the environment in real world situations because the wheelchair's speed is high and participants do not have complete control of the wheelchair.

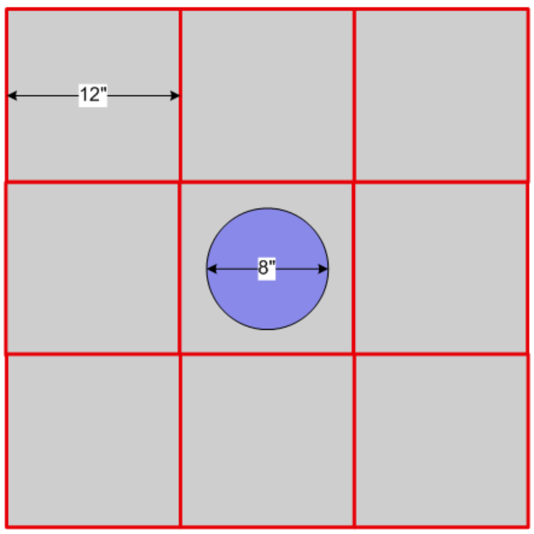

Figure 4-2: Obstacle Placement

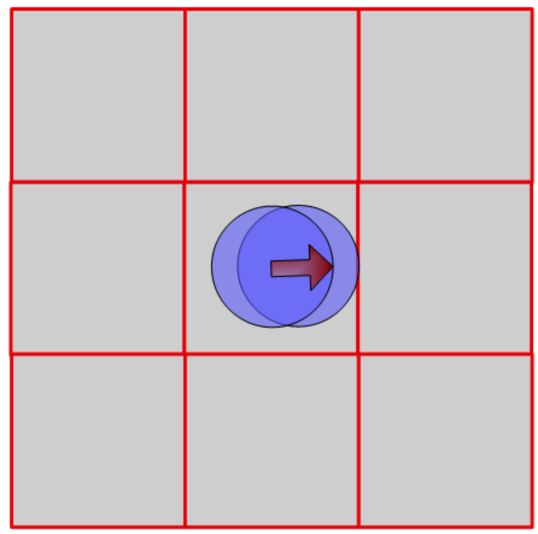

Figure 4-3: Type I Collision

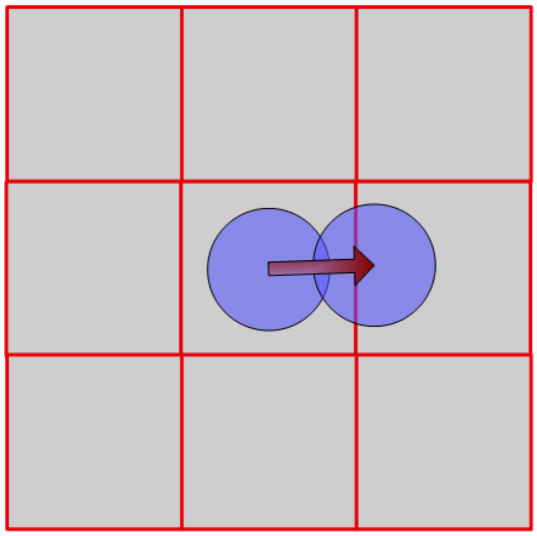

Figure 4-4: Type II Collision

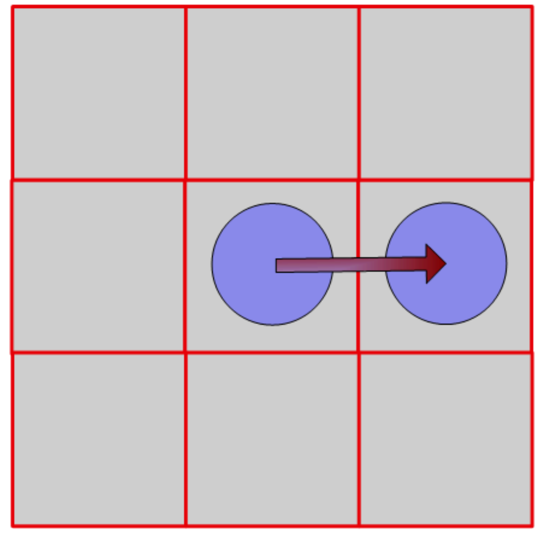

Figure 4-5: Type III Collision

NASA Task Load Index (NASA-TLX): The National Air and Space Administration - Task Load Index (NASA-TLX) questionnaire is a self-reported, survey-based, validated, multidimensional rating procedure [52-55]. The NASA-TLX produces a total workload (TLX-TWL) score based on a weighted average of ratings on six subscales (Effort, Frustration, Performance, Mental Demand, Physical Demand. and Temporal Demand). Out of these six scales three dimensions relate to the demands imposed on the subject (Mental, Physical and Temporal Demand) and three to the interaction of a subject with the task (Effort, Frustration. and Performance).

Mental Demand (TLX-MD) is defined as the mental and perceptual effort (e.g., thinking, deciding, calculating, remembering, searching, maneuvering) required to finish a navigation task. TLX-MD also reflects whether the task was easy or demanding, simple or complex, exacting or forgiving. TLX-MD is measured on a scale of 0-7 where zero is the lowest possible TLX-MD.

Physical Demand (TLX-PD) is defined as the physical activity required (e.g., scanning, pushing, and pulling the cane, maneuvering the joystick, turning, controlling, activating) to finish the navigation task. Further, TLX-PD also represents whether the task was easy or demanding, slow or brisk, slack or strenuous, restful or laborious. TLX-PD is measured on a scale of 0-7, where zero is the lowest possible TLX-PD.

Temporal Demand (TLX-TD) is defined as the time pressure subjects felt due to the rate or pace at which the tasks or task elements occurred. TLX-TD also takes into account the pace of the task progression such as slow and leisurely or rapid and frantic. TLX-TD is measured on a scale of 0-7, where zero is the lowest possible TLX-TD.

Perceived effort (TLX-E) was defined as the amount of work (both mental and physical) participants had to exert to achieve their level of performance. Mental effort and physical effort are different than mental demand and physical demand. Demand is load associated with the task while effort represents the load associated with interaction between the user and the task. TLX-E is measured on a range of 0-7, where zero is the least amount of TLX-E.

Frustration (TLX-F) measures the extent, to which a person feels insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent during the task. TLX-F is measured on a range of 0-7, where zero is the lowest possible TLX-F.

Performance (TLX-P) is defined as how successful participants felt in accomplishing the goals of the task and how satisfied were they with their performance in accomplishing their goals. TLX-P is measured on a scale of 0-7, where zero is the best possible TLX-P.

4.5 DATA ANALYSIS

4.5.1 Statistical Analysis

All analyses were performed using SPSS[5] version 14.0. For each user trial, descriptive statistics were calculated for TCT. Additional descriptive statistics were calculated for the NCT and the NASA-TLX variables in each experimental condition.

The Shapiro-Wilk test was used to check the normality of each variable. If the Shapiro-Wilk statistic was greater than 0.01, data was considered normally distributed. A General Linear Model (GLM) Repeated Measures ANOVA was used for analyses of normally distributed dependent variables with the significance level set at $p < 0.05$. Pairwise comparisons were performed with a standard t-test with a Bonferroni adjustment for multiple comparisons.

Data which were not normally distributed were analyzed using non-parametric tests for related samples. Friedman's test was used to compare the underlying distributions across all three experimental conditions with significance level set at $p < 0.05$. Pairwise comparisons between conditions were performed using the Wilcoxon Signed Ranks test with a significance level set at $p < 0.05$.

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[5] SPSS, Inc., Chicago, IL

Table 4-2 was used to determine the normality of the dependent variables in three experimental conditions.

Table 4-2: Data Normality Test Results

Conditions / Variables	Cane		DSS		Cane&DSS	
	Shapiro-Wilk	Normality	Shapiro-Wilk	Normality	Shapiro-Wilk	Normality
Type I Collisions (NCT-I)	0.003	No	0.0001	No	0.0001	No
Type II Collisions (NCT-II)	0.002	No	0.0001	No	0.0001	No
Type III Collisions (NCT-III)	0.0001	No	0.0001	No	0.0001	No
Total Collisions (NCT-T)	0.23	**Yes**	0.0001	No	0.0001	No
Task Completion Time (TCT)	0.912	**Yes**	0.721	**Yes**	0.573	**Yes**
Mental Demand (TLX-MD)	0.095	**Yes**	0.019	**Yes**	0.016	**Yes**
Physical Demand (TLX-PD)	0.203	**Yes**	0.0001	No	0.0001	No
Temporal Demand (TLX-TD)	0.001	No	0.041	**Yes**	0.103	**Yes**
Performance (TLX-P)	0.018	**Yes**	0.064	**Yes**	0.0001	No
Effort (TLX-E)	0.545	**Yes**	0.001	No	0.007	No
Frustration (TLX-F)	0.011	**Yes**	0.0001	No	0.0001	No
Total Workload (TLX-TWL)	0.21	**Yes**	0.122	**Yes**	0.03	**Yes**

Note: Data is considered normally distributed if $p>0.01$.

4.6 RESULTS

4.6.1 Collisions

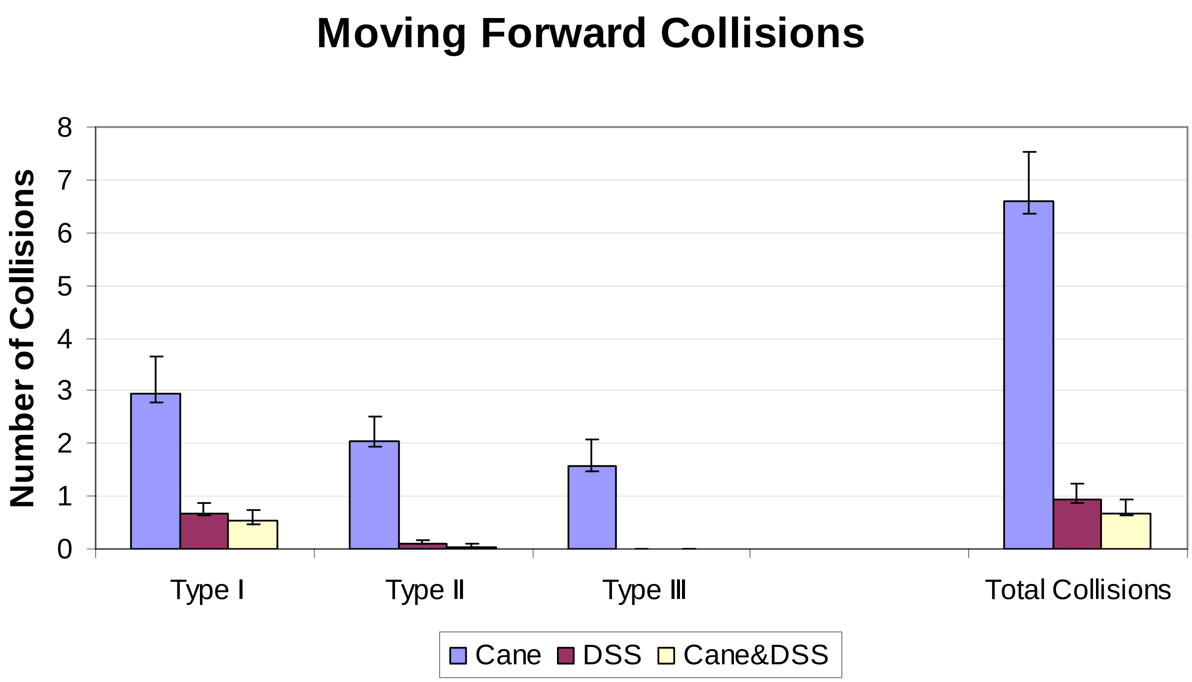


Figure 4-6: Moving Forward Collisions

4.6.1.1 Number of Type I Collisions per Trial

As shown in Table 4-3, the Number of Type I Collisions per Trial (NCT-I) was greatest under the Cane condition with a mean of 2.95 (±3.0). The second largest NCT-I occurred under the DSS condition, with a mean of 0.68 (±0.82). The lowest NCT-I occurred under the Cane&DSS condition, with a mean of 0.53 (±0.964). NCT-I was not normally distributed (Cane: p=0.003; DSS: p=0.0001; DSS+Cane: p=0.0001).

A significant difference existed between conditions (χ^2(2 , N = 19) = 14.926, p=0.001). Participants had significantly more NCT-I under the Cane condition than under the DSS condition (Z=2.942, $p<0.003$) and the Cane&DSS condition (Z=3.256, $p=0.001$). There was not a significant difference in NCT-I between the DSS and Cane&DSS conditions (Z=0.812, $p=0.417$).

Table 4-3: Number of Type I Collisions per Trial (NCT-I)

Condition	Mean (n = 19)	Range
Cane	2.95 (±3.0)	[0, 12]
DSS	0.68 (±0.82)	[0, 2]
Cane&DSS	0.53 (±0.96)	[0, 3]

4.6.1.2 Number of Type II Collisions per Trial

As shown in Table 4-4, the Number of Type II Collisions per Trial (NCT-II) was greatest under the Cane condition with mean of 2.05 (±1.98). The second largest NCT-II occurred under the DSS condition with a mean of 0.11 (±0.31). The lowest NCT-II occurred under the Cane&DSS condition with a mean of 0.05 (±0.23). NCT-II was not normally distributed (Cane: $p=0.002$; DSS: $p=0.0001$; DSS+Cane: $p=0.0001$).

A significant difference existed between conditions ($\chi^2(2, N = 19) = 28.167$, $p=0.0001$). Participants had significantly more NCT-II under the Cane condition than under the DSS condition (Z=3.455, $p=0.001$) and the Cane&DSS condition (Z=3.458, $p=0.001$). There was not a significant difference in NCT-II between the DSS and Cane&DSS conditions (Z=-0.577, $p=0.564$).

Table 4-4: Number of Type II Collisions per Trial (NCT-II)

Condition	Mean (n = 19)	Range
Cane	2.05 (±1.98)	[0, 6]
DSS	0.11 (±0.31)	[0, 1]
Cane&DSS	0.05 (±0.23)	[0, 1]

4.6.1.3 Number of Type III Collisions per Trial

As shown in Table 4-5, the Number of Type III Collisions per Trial (NCT-III) had a mean of 1.56 (±2.12) under the Cane condition, but there were no Type III collisions under either the DSS or Cane&DSS conditions. NCT-III was not normally distributed (Cane: p=0.0001; DSS: p=0.00001; Cane&DSS: p=0.00001).

A significant difference existed between conditions (χ^2(2 , N = 19) = 22.00, p=0.0001). Participants had significantly more NCT-III under the Cane condition than under the Cane&DSS condition (Z=2.965, p=0.003) and the DSS condition (Z=2.965, p=0.003).

Table 4-5: Number of Type III Collisions per Trial (NCT-III)

Condition	Mean (n = 19)	Range
Cane	1.56 (±2.12)	[0, 7]
DSS	0	[0, 0]
Cane&DSS	0	[0, 0]

4.6.1.4 Total Number of Collisions per Trial

As shown in Table 4-6, the Cane condition had the greatest Total Number of Collisions per Trial (NCT-T) with a mean of 6.58 (±4.07) The Cane&DSS condition had the second greatest NCT-T, with a mean of 0.95 (±1.27). The DSS had the lowest NCT-T, with a mean of 0.68 (±1.1). NCT-

T was normally distributed ($p<0.23$) under the Cane condition but was not normally distributed under the DSS and Cane&DSS conditions (DSS: $p<0.0001$; DSS+Cane: $p<0.0001$).

A significant difference existed between conditions ($\chi^2(2\ ,\ N = 19\ ) = 31.303$, $p=0.0001$). Participants had significantly more NCT-T under the Cane condition than under the DSS condition ($Z=-3.731$, $p=0.0001$) and the Cane&DSS condition ($Z=-3.827$, $p<0.0001$). There was not a significant difference in NCT-T between the DSS and Cane&DSS conditions ($Z=-1.221$, $p=0.222$).

Table 4-6: Total Number of Collisions per Trial (NCT-T)

Condition	Mean (n = 19)	Range
Cane	6.59 (±4.07)	[1, 16]
DSS	0.68 (±1.10)	[0, 3]
Cane&DSS	0.95 (±1.27)	[0, 5]

4.6.2 Task Completion Time

As shown in Table 4-7, mean Task Completion Time (TCT) was lowest under the Cane condition at 82.67 (±20.91) seconds. Mean TCT was 91.53 (±18.85) seconds under the DSS condition and was 107.24 (±18.29) seconds under the Cane&DSS condition. Mean TCT was normally distributed under all three conditions (Cane: $p=0.912$; DSS: $p=0.721$; Cane&DSS: $p=0.573$).

There was a statistically significant difference in TCT between conditions ($F[2\ ,\ 36]=9.398$, $p<0.001$). TCT was lower under the Cane condition than under the DSS condition, but this difference was not statistically significant ($p=0.458$). TCT was lower under the Cane condition than under the Cane&DSS condition and this difference was statistically significant ($p=0.002$).

TCT was lower under DSS than under the Cane&DSS condition and this difference was also statistically significant (p=0.016).

Table 4-7: Task Completion Time

Condition	Mean (n = 19)	Range
Cane	82.67 (±20.91)	[48.67, 123.00]
DSS	91.53 (±18.85)	[60.33, 125.00]
Cane&DSS	107.24 (±18.29)	[73.00, 136.33]

4.6.3 National Air and Space Administration –Task Load Index

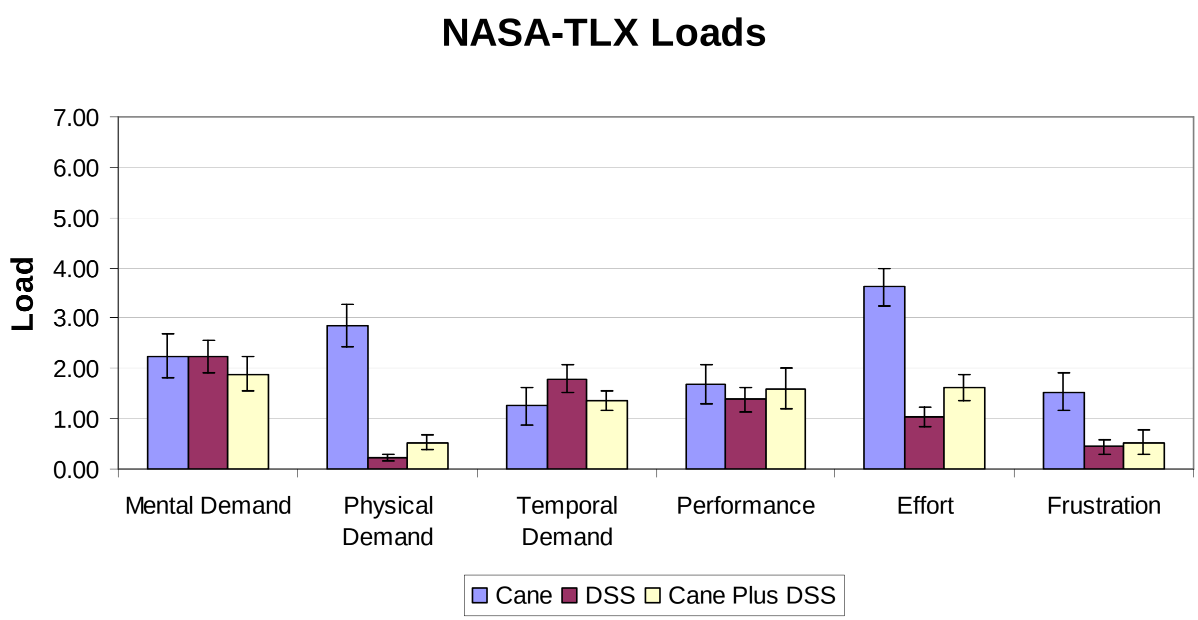


Figure 4-7: NASA-TLX Loads

4.6.3.1 Mental Demand

As shown in Table 4-8, TLX-MD had a mean of 1.89 (±1.45) under the Cane&DSS condition, a mean of 2.22 (±1.40) under the DSS condition and a mean of 2.24 (±1.90) under the Cane condition. TLX-MD was normally distributed under all three conditions (Cane: p=0.10, DSS: p=0.02, and Cane&DSS: p=0.02). There was not a significant difference in TLX-MD between conditions ($F[1.499, 26.983]=0.415$, p=0.606).

Table 4-8: NASA-TLX Mental Demand (TLX-MD)

Condition	Mean (n = 19)	Range
Cane	2.24 (±1.90)	[0, 5.67]
DSS	2.22 (±1.40)	[0, 5.00]
Cane&DSS	1.89 (±1.45)	[0, 5.33]

4.6.3.2 Physical Demand

As shown in Table 4-9, TLX-PD had a mean of 0.22 (±0.39) under the DSS condition, a mean of 0.53 (±0.67) under the Cane&DSS condition and a mean of 2.84 (±1.85) under the Cane condition. TLX-PD was not normally distributed under the Cane condition (p>0.01) but was normally distributed under DSS and Cane&DSS conditions (DSS: p=0.0001, Cane&DSS: p=0.0001).

Table 4-9: NASA-TLX Physical Demand (TLX-PD)

Condition	Mean (n = 19)	Range
Cane	2.84 (±1.85)	[0.40, 6.67]
DSS	0.22 (±0.39)	[0, 1.20]
Cane&DSS	0.53 (±0.67)	[0, 2.40]

A significant difference existed between conditions ($\chi^2(2, N = 19) = 32.21$, p=0.0001). TLX-PD was significantly greater under the Cane condition than under the DSS condition (Z=3.823, p=0.0001) and the Cane&DSS condition (Z=3.825, p<0.0001). TLX-PD was significantly greater under the Cane&DSS condition than under the DSS condition (Z=2.137, p=0.033).

4.6.3.3 Temporal Demand

As shown in Table 4-10, TLX-TD had a mean of 1.26 (±1.58) under the Cane condition, a mean of 1.37(±0.85) under the Cane&DSS condition and a mean of 1.80 (±1.22) under the DSS condition. TLX-TD was not normally distributed under the Cane condition (p=0.001) but was normally distributed under the DSS and Cane&DSS conditions (DSS: p=0.041, Cane&DSS: p=0.103). There was not a significant difference between conditions ($\chi^2(2, N = 19) = 1.38$, p=0.502).

Table 4-10: NASA-TLX Temporal Demand (TLX-TD)

Condition	Mean (n = 19)	Range
Cane	1.26 (±1.58)	[0, 5.07]
DSS	1.80 (±1.22)	[0.27, 5.00]
Cane&DSS	1.37 (±0.85)	[0.13, 2.60]

4.6.3.4 Performance

As shown in Table 4-11, TLX-P had a mean of 1.38 (±1.05) under the DSS condition, a mean of 1.60 (±1.72) under the Cane&DSS condition and a mean of 1.69 (±1.66) under the Cane condition. TLX-P was normally distributed under Cane&DSS condition (p=0.064) but was not normally distributed under Cane or DSS conditions (Cane: p=0.018, DSS: p=0.0001). There was not a significant difference between conditions (χ^2(2 , N = 19) = 1.562, p=0.458).

Table 4-11: NASA-TLX Performance (TLX-P)

Condition	Mean (n = 19)	Range
Cane	1.69 (±1.66)	[0, 5.33]
DSS	1.38 (±1.05)	[0, 3.47]
Cane&DSS	1.60 (±1.74)	[0.13, 6.67]

4.6.3.5 Perceived Effort

As shown in Table 4-12, TLX-E had a mean of 1.04 (±0.88) under the DSS condition, a mean of 1.60 (±1.12) under the Cane&DSS condition and a mean of 3.62 (±1.60) under the Cane condition. TLX-E was normally distributed under the Cane condition (p=0.545) but was not normally distributed under DSS or Cane&DSS (DSS: p=0.001, Cane&DSS: p=0.007). There was a significant difference between conditions (χ^2(2 , N = 19) = 26.493, p=0.0001). TLX-E was significantly greater under the Cane condition than under the DSS condition (Z=3.784, p=0.0001) and the Cane&DSS condition (Z=3.583, p=0.0001). TLX-E under the Cane&DSS condition was significantly greater than under the DSS condition (Z=2.096, p=0.036.).

Table 4-12: NASA-TLX Effort (TLX-E)

Condition	Mean (n = 19)	Range
Cane	3.62 (±1.60)	[1.33, 7.00]
DSS	1.04 (±0.88)	[0.27, 3.47]
Cane&DSS	1.60 (±1.12)	[0.27, 4.66]

4.6.3.6 Frustration

As shown in Table 4-13, TLX-F had a mean of 0.45 (±0.64) under the DSS condition, a mean of 0.53 (±1.04) under the Cane&DSS condition and a mean of 1.53 (±1.60) under the Cane condition. TLX-F was normally distributed under the Cane condition (*p*=0.11) but was not normally distributed under DSS or Cane&DSS (DSS: *p*=0.0001, Cane&DSS: *p*=0.0001). A significant difference existed between conditions (χ^2(2 , N = 19) = 10.226, *p*=0.006). TLX-F was significantly higher under the Cane condition than under the DSS condition (Z=2.536, *p*=0.011) and the Cane&DSS condition (Z=2.446, *p*=0.014). TLX-F under the Cane&DSS and DSS conditions was not significantly different (Z=2.051, *p*=0.959).

Table 4-13: NASA-TLX: Frustration

Condition	Mean (n = 19)	Range
Cane	1.53 (±1.60)	[0, 5.33]
DSS	0.45 (±0.64)	[0, 2.20]
Cane&DSS	0.53 (±1.04)	[0, 3.80]

4.6.3.7 Total Workload

As shown in Table 4-14, Total Workload (TLX-TWL) had a mean of 7.12 (±2.84) under the Cane&DSS condition, a mean of 7.52 (±3.82) under the DSS condition and a mean of 13.17 (±3.88) under the Cane condition. The maximum possible value of the TLX-TWL was 21. TLX-TWL was normally distributed under all three experimental conditions (Cane: *p*=0.21, DSS: *p*=0.122, Cane&DSS: *p*=0.03). There was significant difference between conditions (*F*[1.453, 25.157]=28.242, *p*=0.0001). TLX-TWL was significantly higher under the Cane condition than the DSS condition (*p*=0.0001) and the Cane&DSS condition (*p*=0.0001). TLX-TWL was higher under the DSS condition than under the Cane&DSS condition but this difference was not statistically significant (p=0.95).

Table 4-14: NASA-TLX Total Workload (TLX-TWL)

Condition	Mean (n = 19)	Range
Cane	13.17 (±3.88)	[7.47, 19.60]
DSS	7.52 (±3.82)	[3.20, 16.47]
Cane&DSS	7.12 (±2.84)	[3.33, 12.20]

4.7 DISCUSSION

4.7.1 Collisions

In keeping with our hypothesis, participants had significantly more collisions when using just the cane than when using the DSS alone. Most of the collisions when using the cane alone occurred primarily because participants did not have an adequate understanding of the wheelchair's size and dynamics. Second, participants could not maintain the coordination between the wheelchair speed and the rate of obstacle scanning with cane; because of this even after detecting the obstacles, participants could not bring the wheelchair to stop or change the direction before hitting the obstacles. Third, the stroke of scanning was not wide enough to detect the obstacles in the corners of the wheelchair.

When using DSS alone or in combination with the cane, most collisions occurred primarily because sensor stop threshold was not appropriate in few sectors (sector 5, sector 6, sector 13 and sector 14) around the wheelchair. Secondly, DSS was unable to detect the obstacles when they were present in the no sensor coverage area behind the wheelchair. The DSS reduced the severity of collisions; nearly all collisions that occurred when the DSS was active were of the lowest severity (Type I). The more severe collisions (most Type II collisions and all Type III collisions) occurred when participants were using the cane alone. Type III collisions were prevented when using DSS because the sensors were able to slow or stop the chair before a collision occurred.

When the DSS is active, the bumpers are activated whenever the wheelchair touches an obstacle, stopping the wheelchair immediately and limiting potential damage. In present experiments since obstacles were light weight cardboard tubes the pressure applied on the bumpers by these obstacles was below bumper activation threshold.

4.7.2 Task Completion Time

As hypothesized, TCT was lowest under the Cane condition. However, as shown in Figure 4-8, this performance was achieved at the expense of hitting significantly more obstacles. TCT was increased when using DSS because the speed of the wheelchair was reduced in presence of the obstacles around the wheelchair to avoid collisions, so participants took more time to complete the trial. Further, sonar sensor cross talk occasionally stopped the wheelchair unnecessarily; this added more time. TCT was greater when using the cane and DSS together than when using DSS alone due to the additional time added by retrieving the cane, scanning the environment and stowing the cane, even though this allowed participants to navigate around obstacles with fewer joystick maneuvers.

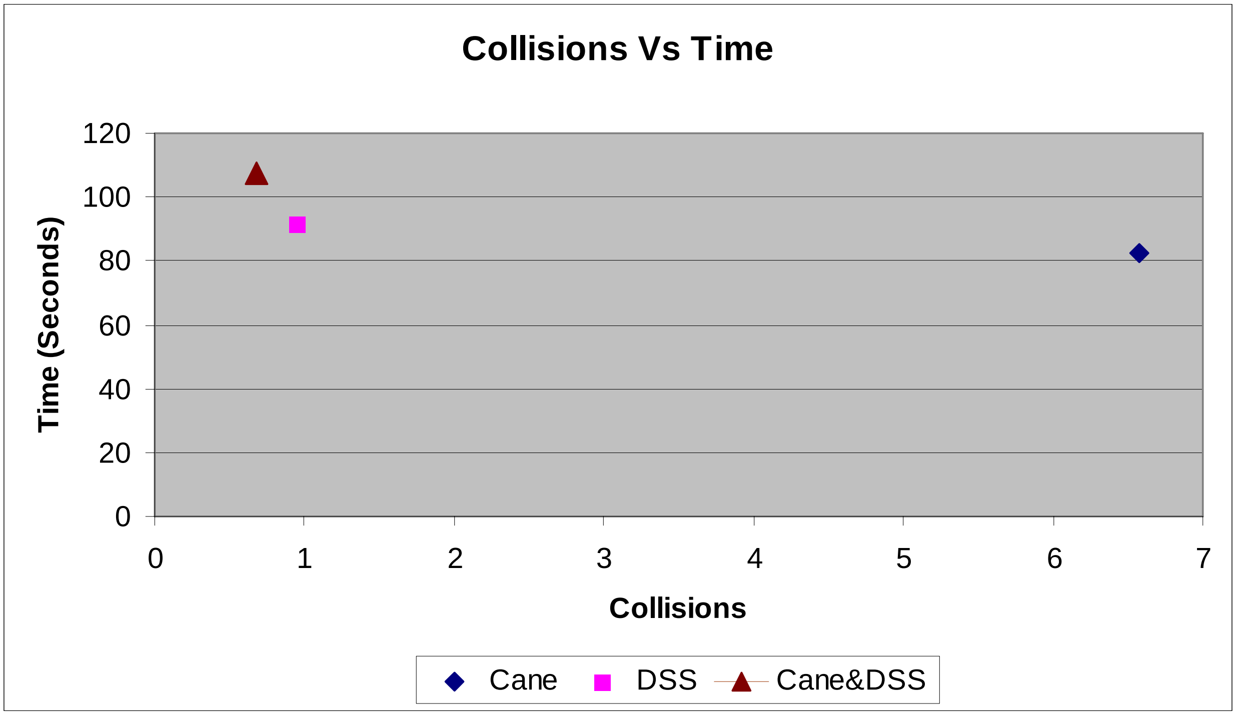


Figure 4-8: Collisions Vs Task Completion Time

4.7.3 Physical Demand

As hypothesized, physical demand was significantly higher when using the cane alone. Participants felt additional physical demand when using the cane because they had to continuously scan the environment to detect obstacles and, upon detection, change the direction of the wheelchair to avoid a collision. Physical demand was reduced when using the cane in combination with DSS since participants relied on the DSS for collision avoidance so they did not use the cane in this condition as much as they did in when using cane alone.

4.7.4 Mental Demand

The hypothesis that mental demand would be greater when using the cane alone was not supported. There was not a significant difference between conditions. In addition, mental demand was not particularly high under any condition. Able bodied participants never used the cane or the DSS before so they had to learn to use these devices for navigation assistance and that may be the reason they did not experience any difference in the mental demand.

4.7.5 Frustration

As hypothesized, frustration was significantly higher when using the cane alone. Using the cane caused frustration because participants felt insecure about hitting obstacles. It should be noted, however, that frustration was still low (1.53 on a scale of 0 to 7) under the cane condition so it is unclear whether frustration was actually problematic.

4.7.6 Perceived Effort

As hypothesized, effort when using the cane alone was significantly higher because participants had to put extra physical effort in scanning of the environment by cane. Further, there was mental effort involved in learning to coordinate both hands while navigating towards the target sound. Mental effort when using the cane is likely to decline as people learn to coordinate both hands (scanning and maneuvering). Further, the physical effort component can be reduced by teaching efficient environment scanning strategies.

4.7.7 Total Workload

As hypothesized, total workload was significantly lower when using the cane alone. When using the cane alone, physical demand and effort were responsible for 49% of TLX-TWL. Further, mental demand accounted for 17% of TLX-TWL and frustration was responsible for 12%.

4.8 CONCLUSIONS

Nearly all hypotheses were supported by the data. The DSS reduced the number of collisions and the severity of collisions but did not increase the time required to complete navigation tasks. Participants were not experienced wheelchair users or experienced cane users, so it is not surprising that using both without assistance produced the greatest perceived workload. The fact that all participants were young and able-bodied may have contributed to the relatively low workload reported for all three conditions.

5.0 STUDY 2: ABLE BODIED SUBJECTS (BACKWARD DRIVING)

5.1 INTRODUCTION

Many non-institutionalized individuals with mobility impairments have been shown to improve their performance and satisfaction in activities of daily living (ADL) by using a powered wheelchair [10, 56]. Many ADL such as toileting, dressing, feeding, transferring, getting in and out of public transportation, getting in and out of elevators, and ascending or descending ramps require a person to maneuver the wheelchair in confined spaces [56, 57]. In order to access these confined spaces, drivers may be required to drive in reverse or perform maneuvers similar to parallel parking [57]. Many wheelchair users have limited neck range of motion and have difficulty looking backward when backing up in confined spaces. This creates unsafe driving practices and can lead to collisions which may result in personal injury or property damage [17, 18, 57].

Driving backward is difficult because of poor reverse directional stability of powered wheelchairs [58]. Caster orientation and driving speed can vary the reverse movement direction of the powered wheelchair [58]. This unpredictable dynamics require multiple joystick maneuvers to achieve the desired movement direction.

A powered wheelchair data logger study showed that, for non-institutionalized powered wheelchair users, 13% of their total travel distance is driven backwards [59]. Distance traveled between stops can provide evidence of the difficulty people experience when moving backward. Distance traveled between stops when moving forward was 11.65 meters and 2.73 meters when driving backwards [59]. Speed of travel forward and backward for this population was not significantly different.

Smart wheelchair technologies have shown advantages in reducing the number of collisions in comparison to conventional navigation assistance methods [5, 6, 32, 60, 61], but no study has evaluated a person's performance on a navigation task which requires backward driving. The study described in this section used the same able-bodied individuals who took part in the study of forward driving described in Chapter 4. Participants wore blindfolds to simulate complete blindness.

5.2 HYPOTHESES AND SPECIFIC AIMS

The purpose of this study was to determine if the DSS provides effective independent mobility to able bodied individuals when they are simulating the condition of people with visual and mobility impairments.

Specific Aim 1. To evaluate the effectiveness of the DSS versus cane on a backward moving navigation task based on quantitative measures such as number of collisions and task completion time. Following hypotheses were associated with the specific aim 1:

Hypothesis Q1. People will have fewer collisions when using the DSS than when using a cane.

Hypothesis Q2. The average time of completion for a task will be greater when using the DSS in comparison to a cane.

Specific Aim 2. To evaluate the subjective workload associated with the use of the DSS on a backward moving navigation task and compare it with the subjective workload associated with the use of a cane on the similar navigation task. Following hypotheses were associated with the specific aim 2:

Hypothesis S1. Perceived physical demand in a given navigation task will be lower when using the DSS than when using a cane.

Hypothesis S2. Perceived mental demand will be higher when using the DSS than when using a cane.

Hypothesis S3. Frustration when using the DSS will be lower than when using a cane.

Hypothesis S4. Perceived effort when using the DSS will be lower than when using a cane.

Hypothesis S5. TWL when using the DSS will be lower than when using a cane.

Specific Aim 3. To evaluate the performance and robustness of the DSS based on the quantitative measures (e.g. number of collisions, task completion time, number of system resets required during the trials, errors in the architecture) and subjective measures (e.g. workload, users' recommendation, investigators observation of users' performance), and based on the results, determine the changes required in the hardware (e.g., electronics and sensor housings, mountings), software (e.g., slow threshold, stop threshold) and user interface (e.g., auditory feedback, visual feedback).

5.3 SUBJECTS

All the participants who participated in Study 1 also participated in Study 2.

5.4 METHODS

5.4.1 Seating and Positioning

Participants were given a 15 minute break during the transition from Study 1 to Study 2. In the backward driving study the seating and positioning of the participants was the same as the blindfolded forward driving study.

5.4.2 Training

Participants were first introduced to reverse driving by teaching various joystick maneuvering skills to move in desired backwards direction. Participants' backward driving skills were tested without blindfolds on two test courses (see Appendix A.1) designed to enhance participants' familiarity with the wheelchair's dynamics and ability to maneuver in tight spaces. Participants traversed these courses driving backwards until they were able to complete the courses without hitting any obstacles. While driving on the test course, participants did not have support from the DSS proximity sensors but the bumpers were active and participants were not blindfolded; if a participant hit the sidewalls, the bumpers would stop the wheelchair.

Participants were then blindfolded and their blindfolds were adjusted such that participants did not get any visual input from the environment. Participants were then given instructions on ways to use the cane to scan the area behind the wheelchair for obstacles while driving backwards. Participants used their dominant hand to operate the joystick while the other hand was used for scanning the area behind the wheelchair with the cane. Participants were given two obstacle courses to practice navigation.

Participant's blindfolds were removed and they received an explanation about the auditory feedback provided by the DSS when it encountered obstacle in the back of the wheelchair. When participants demonstrated that they understood the DSS and its operation when driving backwards, they were asked to approach obstacles placed behind the wheelchair and observe the wheelchair's response to obstacles. Participants approached the obstacle from various angles while driving backwards to become familiar with the rear obstacle stop thresholds.

Participants were then blindfolded and given two obstacle courses to navigate while driving backwards using assistance from the DSS. Investigators observed the performance of the participants and instructed them on various navigation skills to effectively use the assistance from the DSS. These training courses gave participants an understanding of the obstacle distance thresholds (safe, slow, and stop) of the DSS when driving backwards.

The last set of training activities involved the use of cane and the DSS together. Participants were given instructions about how to use the cane and the DSS together to optimize their navigation performance while driving backwards. They were instructed to use the cane primarily to determine the location of obstacles around the wheelchair when the DSS stopped the wheelchair. Participants were instructed to hold the cane on their lap or in a position where it did not interfere with the sonar and infrared sensors when it was not being used. Participants were given two training obstacle courses in this condition to familiarize themselves with the use of a cane with the DSS when driving backwards.

5.4.3 Protocol

Participants completed three trials in each experimental condition same as in forward driving study protocol. In each trial, participants were blindfolded and asked to reach a goal indicated by a sound source while driving backwards. In each trial the obstacle course was assigned randomly from the obstacle courses shown in Appendix A.3 to prevent subjects from learning the obstacle courses. No two obstacle courses in the nine trials of the backward driving study were similar. The same protocol used in Study 1 (see Section 4.4.2.4) was followed.

5.5 DATA ANALYSIS

The same approach to statistical analysis used in Study 1 (see Section 4.5) was used. Table 5-1 was used to determine the normality of the dependent variables in three experimental conditions.

Table 5-1: Data Normality (Blindfolded Reverse Driving Protocol)

Conditions / Variables	Cane		DSS		Cane&DSS	
	Shapiro-Wilk	Normality	Shapiro-Wilk	Normality	Shapiro-Wilk	Normality
Type I Collision (NCT-I)	0.111	**Yes**	0.0001	No	0.001	No
Type II Collision (NCT-II)	0.001	No	0.0001	No	0.0001	No
Type III Collision (NCT-III)	0.0001	No	0.0001	No	0.0001	No
Total Collisions (NCT-T)	0.335	**Yes**	0.0001	No	0.001	No
Trial Completion Time (TCT)	0.074	**Yes**	0.010	**Yes**	0.085	**Yes**
Mental Demand (TLX-MD)	0.117	**Yes**	0.049	**Yes**	0.664	**Yes**
Physical Demand (TLX-PD)	0.045	**Yes**	0.0001	No	0.001	No
Temporal Demand (TLX-TD)	0.0001	No	0.057	**Yes**	0.036	**Yes**
Performance (TLX-P)	0.003	No	0.148	**Yes**	0.010	**Yes**
Effort (TLX-E)	0.960	**Yes**	0.034	**Yes**	0.019	**Yes**
Frustration (TLX-F)	0.096	**Yes**	0.0001	No	0.001	No
Total Workload (TLX-TWL)	0.121	**Yes**	0.778	**Yes**	0.782	**Yes**

5.6 RESULTS

5.6.1 Collisions

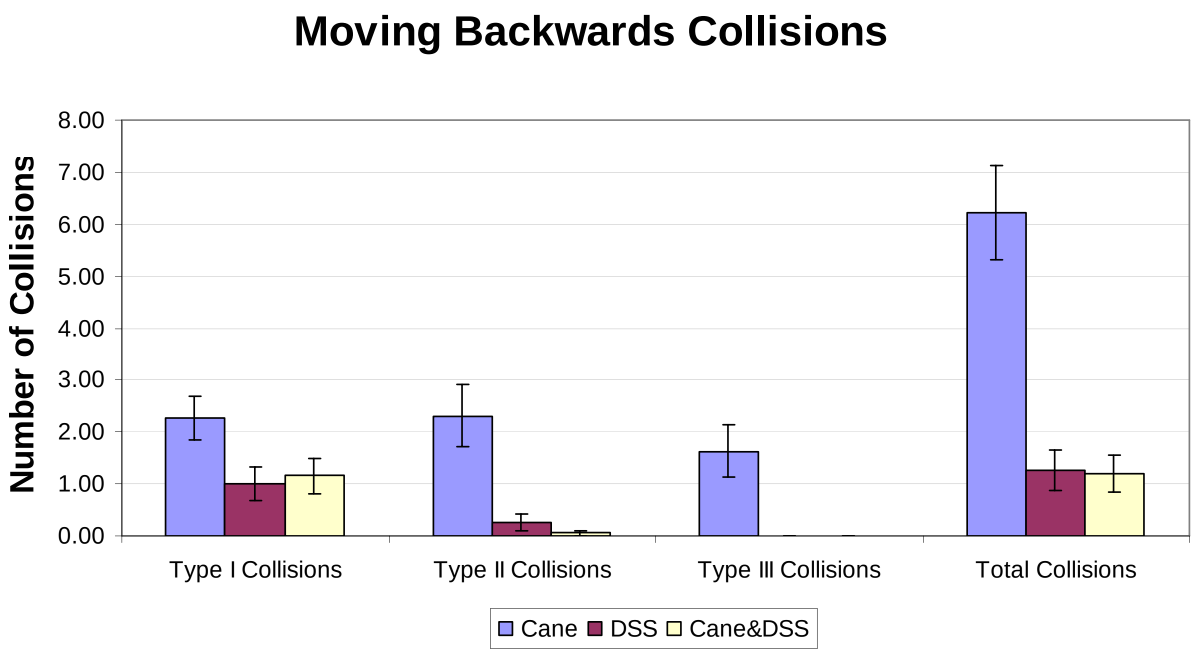


Figure 5-1: Moving Backwards Collisions

5.6.1.1 Number of Type I Collisions per Trial

As shown in Table 5-2, the Number of Type I Collisions per Trial (NCT-I) was greatest under the Cane condition with a mean of 2.26 (±1.85) per trial. The second largest NCT-I occurred under the Cane&DSS condition, with a mean of 1.16 (±1.50). The lowest NCT-I occurred under the DSS condition, with a mean of 1.00 (±1.45). NCT-I was not normally distributed (Cane: p=0.11; DSS: p=0.0001; DSS+Cane: p=0.0001).

A significant difference existed among experimental conditions (χ^2[2 , 18] = 8.035, p=0.018). Participants had significantly more NCT-I under the Cane condition than under the

DSS condition (Z=2.352, p=0.019) and the Cane&DSS condition (Z=2.278, p=0.023). There was not a significant difference in NCT-I between the DSS and Cane&DSS conditions (Z=0.544, p=0.587).

Table 5-2. Number of Type I Collisions per Trial (NCT-I)

Condition	Mean (n = 19)	Range
Cane	2.26 (±1.85)	[0, 6]
DSS	1.00 (±1.45)	[0, 4]
Cane&DSS	1.16 (±1.50)	[0, 5]

5.6.1.2 Number of Type II Collisions per Trial

As shown in Table 5-3, the Number of Type II Collisions per Trial (NCT-II) was greatest under the Cane condition with a mean of 2.32 (±2.60) per trial. The second largest NCT-II occurred under the DSS condition with a mean of 0.26 (±0.65). The lowest NCT-II occurred under the Cane&DSS condition with a mean of 0.05 (±0.23). NCT-II was not normally distributed (Cane: p=0.001; DSS: p=0.0001; DSS+Cane: p=0.0001).

A significant difference existed among driving conditions ($\chi^2(2, N = 19) = 19.633$, p=0.0001). Participants had significantly more NCT-II under the Cane condition than under the DSS condition (Z=2.752, p=0.006) and the Cane&DSS condition (Z=3.329, p=0.001). There was not a significant difference in NCT-II between the DSS and Cane&DSS conditions (Z=-1.30, p=0.194).

Table 5-3. Number of Type II Collisions per Trial (NCT-II)

Condition	Mean (n = 19)	Range
Cane	2.32 (±2.60)	[0, 8]
DSS	0.26 (±0.65)	[0, 2]
Cane&DSS	0.05 (±0.23)	[0, 1]

5.6.1.3 Type III Collisions

As shown in Table 5-4, the Number of Type III Collisions per Trial (NCT-III) had a mean of 1.63 (±2.17) Type III Collisions under the Cane condition, but there were no Type III Collisions under either the DSS or Cane&DSS conditions. NCT-III was not normally distributed (Cane: p=0.0001; DSS: p=0.0001; Cane&DSS: p=0.0001).

A significant difference existed between conditions (χ^2(2 , N = 19) = 22.00, p=0.0001). Participants had significantly more NCT-III under the Cane condition than under the Cane&DSS condition (Z=2.952, p=0.003) and the DSS condition (Z=2.952, p=0.003).

Table 5-4. Number of Type III Collisions per Trial (NCT-T)

Condition	Mean (n = 19)	Range
Cane	1.63 (±2.17)	[0, 8]
DSS	0(±0)	[0, 0]
Cane&DSS	0(±0)	[0, 0]

5.6.1.4 Total Collisions:

As shown in Table 5-5, the Cane condition had the greatest Total Number of Collisions per Trial (NCT-T) with a mean of 6.21 (±3.94) The DSS condition had the second greatest NCT-T, with a mean of 1.26 (±1.76). The Cane&DSS had the lowest NCT-T, with a mean of 1.21 (±1.55).

NCT-T under the Cane condition was normally distributed (p=0.35) but was not normally distributed for the DSS and Cane&DSS conditions (DSS: p<0.0001; Cane&DSS: p<0.0001).

A significant difference existed between conditions (χ^2(2 , N = 19) = 21.848, p=0.0001). Participants had significantly greater NCT-T under the Cane condition than under the DSS condition (Z=3.233, p=0.001) and the Cane&DSS condition (Z=3.525, p<0.0001). There was not a significant difference in NCT-T between the DSS and Cane&DSS conditions (Z=0.052, p=0.959).

Table 5-5: Total Collisions (Moving Backwards)

Condition	Mean (n = 19)	Range
Cane	6.21 (±3.94)	[1, 14]
DSS	1.26 (±1.76)	[0, 6]
Cane&DSS	1.21 (±1.55)	[0, 5]

5.6.2 Task Completion Time

As shown in Table 5-6, mean Task Completion Time (TCT) was lowest under the Cane condition at 93.75 (±32.20) seconds. Mean TCT was 96.81 (±27.46) seconds under the Cane&DSS condition and was 98.41 (±46.36) seconds under the DSS condition. TCT was normally distributed under all three conditions (Cane: p=0.912; DSS: p=0.721; Cane&DSS: p=0.573). There was not a statistically significant difference between conditions (χ^2[2 , 36]=0.089, p=0.915).

Table 5-6. Task Completion Time

Condition	Mean (n = 19)	Range
Cane	93.75 (±32.20)	[52.67, 153.00]
DSS	98.49 (±46.36)	[35.67, 234.67]
Cane&DSS	96.81 (±27.46)	[61, 173.33]

5.6.3 National Air and Space Administration – Task Load Index

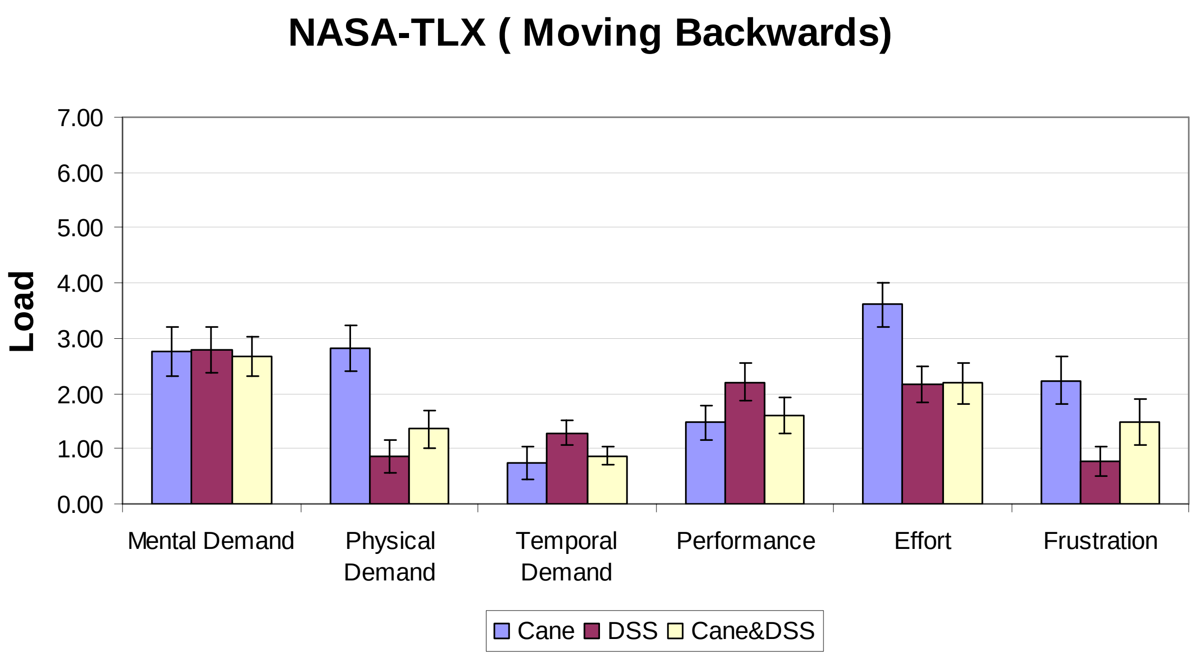


Figure 5-2: NASA-TLX Loads (Moving Backwards)

5.6.3.1 Mental Demand

As shown in Table 5-7, TLX-MD condition had a mean of 2.67 (±1.53) under the Cane&DSS, a mean of 2.75 (±1.93) under the Cane condition and 2.78 (±1.79) under the DSS condition. TLX-MD was normally distributed under all three conditions (Cane: p=0.117, DSS: p=0.049, and

Cane&DSS: p=0.664). There was not a significant difference between conditions (χ^2[2 , 36]=0.048, p=0.954).

Table 5-7: NASA-TLX Mental Demand (TLX-MD)

Condition	Mean (n = 19)	Range
Cane	2.75 (±1.93)	[0, 6.33]
DSS	2.78 (±1.79)	[0.47, 6.33]
Cane&DSS	2.67 (±1.53)	[0.27, 6]

5.6.3.2 Physical Demand

As shown in Table 5-8, TLX-PD had a mean of 0.86 (±1.35) under the DSS condition, a mean of 1.36(±1.46) under the Cane&DSS condition and a mean of 2.82 (±1.83) under the Cane condition. TLX-PD was normally distributed under the Cane condition (p=0.045) but was not normally distributed under the DSS and Cane&DSS conditions (DSS: p=0.0001, Cane&DSS: p=0.001).

A significant difference existed between conditions (χ^2(2 , N = 19) = 18.478, p=0.0001). TLX-PD was significantly greater under the Cane condition than under the DSS condition (Z=2.875, p=0.004) and the Cane&DSS condition (Z=2.770, p=0.006). There was not a significant difference in TLX-PD between the DSS and the Cane&DSS conditions (Z=1.633, p=0.102).

Table 5-8: NASA-TLX Physical Demand (TLX-PD)

Condition	Mean (n = 19)	Range
Cane	2.82 (±1.83)	[0.60, 6.00]
DSS	0.86 (±1.35)	[0, 5.67]
Cane&DSS	1.36 (±1.46)	[0, 6.33]

5.6.3.3 Temporal Demand

As shown in Table 5-9, TLX-TD had a mean of 0.74 (±1.29) under the Cane condition, a mean of 0.87 (±0.70) under the Cane&DSS condition and a mean of 1.29 (±0.99) under the DSS condition. TLX-TD was not normally distributed under the Cane condition (p=0.0001) but was normally distributed under the DSS and Cane&DSS conditions (DSS: p=0.057, Cane&DSS: p=0.036).

There was significant difference between conditions ($\chi^2(2, N = 19) = 10.941$, p=0.004). TLX-TD was significantly greater under the DSS condition than under the Cane condition (Z=2.402, p=0.016) and the Cane&DSS condition (Z=2.432, p=0.015). There was no significant difference in TLX-TD between the Cane and the Cane&DSS condition (Z=0.828, p=0.408).

Table 5-9: NASA-TLX Temporal Demand (TLX-TD)

Condition	Mean (n = 19)	Range
Cane	0.74 (±1.29)	[0, 4.53]
DSS	1.29 (±0.99)	[0, 4.00]
Cane&DSS	0.87 (±0.70)	[0, 2.93]

5.6.3.4 Performance

As shown in Table 5-10, TLX-P had a mean of 1.47 (±1.31) under the Cane condition, a mean of 1.60 (±1.44) under the Cane&DSS condition and a mean of 2.21 (±1.54) under the DSS condition. TLX-P was normally distributed under the DSS condition (p=0.148) but was not normally distributed under the Cane or Cane&DSS conditions (Cane: p=0.003, DSS: p=0.010).

There was a marginally significant difference between conditions ($\chi^2(2, N = 19) = 5.939$, p=0.051). TLX-P was better under the Cane condition than under the DSS condition (Z=2.002, p=0.056). There was no significant difference between the performance reported by the participants in the Cane and the Cane&DSS condition (Z=0.928, p=0.516). There was no significant difference between the performance reported by the participants in the DSS and the Cane&DSS condition (Z=1.201, p=0.218).

Table 5-10: NASA-TLX Performance (TLX-P)

Condition	Mean (n = 19)	Range
Cane	1.47 (±1.31)	[0, 5.33]
DSS	2.21 (±1.54)	[0, 5.33]
Cane&DSS	1.60 (±1.44)	[0, 5.33]

5.6.3.5 Perceived Effort

As shown in Table 5-11, TLX-E had a mean of 2.18 (±1.42) under the DSS condition, a mean of 2.18 (±1.59) under the Cane&DSS condition and a mean of 3.61 (±1.73) under the Cane condition. TLX-E was normally distributed under all the experimental conditions (Cane: p=0.960, DSS: p=0.034, Cane&DSS: p=0.019).

There was significant difference existed between conditions ($\chi^2(2, N = 19) = 10.551$, p=0.005). TLX-E was significantly greater under the Cane condition than under the DSS condition (Z=2.702, p=0.007) and the Cane&DSS condition (Z=2.533, p=0.011). There was not a significant difference in TLX-E between the DSS condition and the Cane&DSS condition (Z=0.047, p=0.962).

Table 5-11: NASA-TLX Effort (TLX-E)

Condition	Mean (n = 19)	Range
Cane	3.61 (±1.73)	[0.4, 7.00]
DSS	2.18 (±1.42)	[0.53, 5.33]
Cane&DSS	2.18 (±1.59)	[0.4, 5.33]

5.6.3.6 Frustration

As shown in Table 5-12, TLX-F had a mean of 0.76 (±1.19) under the DSS condition, a mean of 1.49 (±1.81) under the Cane&DSS condition and a mean of 2.23 (±1.87) under the Cane condition. TLX-F was normally distributed under the Cane condition (p=0.096) but was not normally distributed under the DSS or Cane&DSS conditions (DSS: p=0.0001, Cane&DSS: p=0.001).

A significant difference existed between conditions (χ^2(2 , N = 19) = 10.140, p=0.006). TLX-F was significantly higher under the Cane condition than under the DSS condition (Z=3.067, p=0.002) and the Cane&DSS condition (Z=2.040, p=0.041). TLX-F was not significantly different under the Cane&DSS and DSS conditions (Z=1.687, p=0.092).

Table 5-12: NASA-TLX Frustration (TLX-F)

Condition	Mean (n = 19)	Range
Cane	2.23 (±1.87)	[0, 7]
DSS	0.76 (±1.19)	[0, 4.80]
Cane&DSS	1.49 (±1.81)	[0, 5.33]

5.6.3.7 Total Workload

As shown in Table 5-13, Total Workload (TLX-TWL) had a mean of 10.08 (±3.93) under the DSS condition, a mean of 10.16 (±4.46) under the Cane&DSS condition and a mean of 13.62

(±4.76) under the Cane condition. TLX-TWL was normally distributed under all three experimental conditions (Cane: p=0.121, DSS: p=0.778, Cane&DSS: p=0.782).

There was significant difference in TLX-TWL across conditions (χ^2[2, 36]=7.931, p=0.001). TLX-TWL was significantly higher under the Cane condition than under the DSS condition (p=0.026) and the Cane&DSS condition (p=0.011). The was not a statistically significant between the DSS condition and the Cane&DSS condition (p=0.99).

Table 5-13: NASA-TLX Total Workload (TLX-TWL)

Condition	Mean (n = 19)	Range
Cane	13.62 (±4.76)	[2.53, 20.0]
DSS	10.08 (±3.93)	[3.80, 18.20]
Cane&DSS	10.16 (±4.46)	[3.07, 20.00]

5.7 DISCUSSION

5.7.1 Collisions

As we hypothesized, results from this study indicated that the DSS will promote safe navigation by reducing the number and severity of collisions. Participants had significantly more Type I, Type II and Type III collisions when using just the cane than when using the cane in combination with the DSS or when using the DSS alone. Most of the collisions when using the cane alone occurred because participants could not devise a good strategy to scan the obstacles behind the wheelchair while driving backwards and were not able to detect the obstacles in time to stop the wheelchair.

Most of the collisions that occurred when using the DSS were of very low severity (mainly Type I). The programmed sensor stop threshold was not appropriate when obstacles were present behind the wheelchair, allowing Type I collisions to occur when participants were turning and the rear bumper came in contact with the obstacles. All Type II collisions that occurred when using the DSS occurred because a certain area behind the wheelchair did not have adequate coverage from the sensors.

5.7.2 Task Completion Time

We hypothesized that using the DSS would increase TCT in comparison to using the cane only, but results indicated that this did not happen. As shown in Figure 5-3, TCT was slightly lower with the cane alone, but this performance was achieved at the expense of hitting significantly more obstacles.

One reason for the lack of difference in TCT is that participants had difficulty scanning for obstacles behind the wheelchair using the cane, so they drove slowly to avoid the obstacles behind the wheelchair and made multiple stops. TCT was higher with the DSS primarily because auditory feedback from the wheelchair did not enable the user to identify the exact position of obstacles around the wheelchair. In addition, crosstalk between the sonar sensors made the wheelchair stop in instances where there were no obstacles, which caused participants to steer in the wrong direction and resulted in more time and effort. Finally, the DSS's inability to pass through narrow spaces when moving backwards made this navigation task difficult for the participants and added more time.

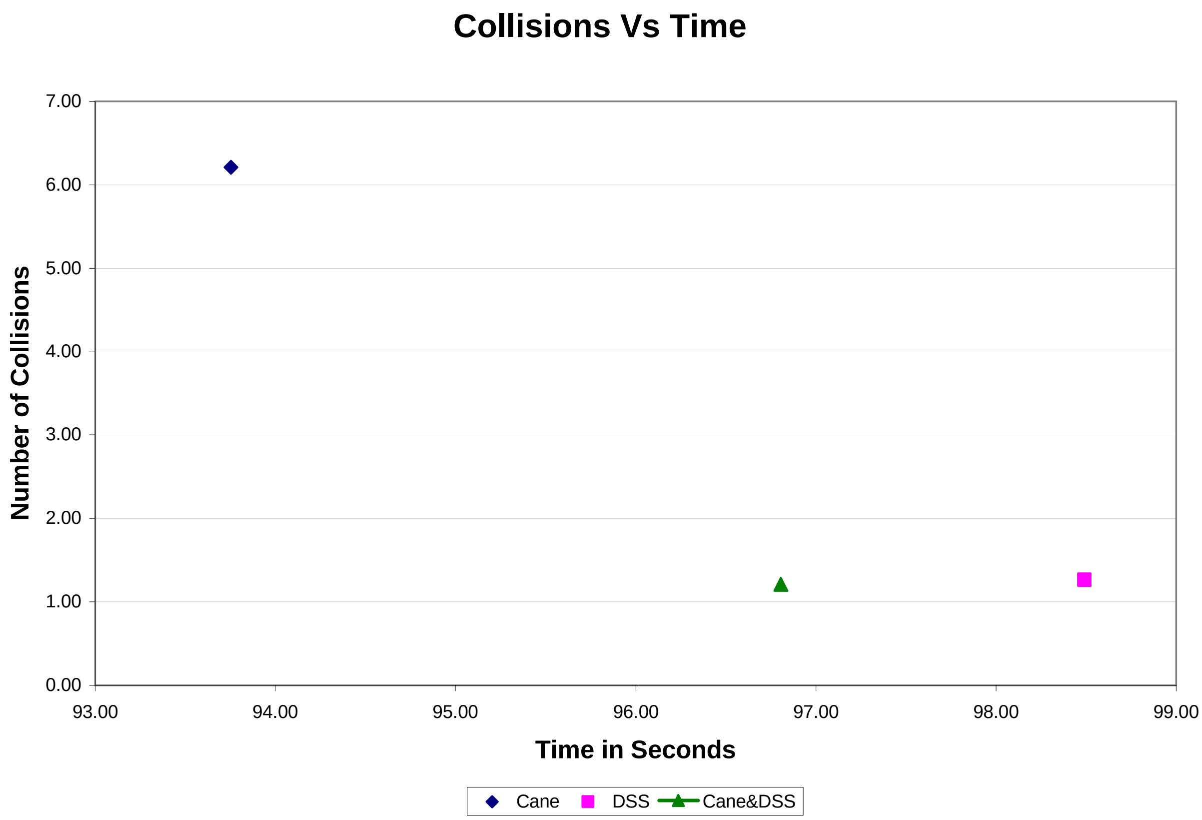


Figure 5-3: Collisions Vs Task Completion Time

5.7.3 Physical Demand

As hypothesized, physical demand was significantly higher when using the cane alone. Participants felt additional physical demand when using the cane because they had to continuously turn themselves backwards and scan the area behind the wheelchair while driving the wheelchair with the joystick mounted in the front of the wheelchair. Physical demand was reduced when using the cane in combination with DSS since participants relied on the DSS for collision avoidance so they did not use the cane in this condition as much as they did in when using cane alone.

5.7.4 Mental Demand

The hypothesis that mental demand would be greater when using the cane alone was not supported. There was not a significant difference between conditions. Able bodied participants never used the cane or the DSS before so they had to learn to use these devices for navigation assistance and that may be the reason they did not experience any difference in the mental demand.

5.7.5 Frustration

As hypothesized, participants reported far greater levels of frustration when using the cane alone. Using the cane caused frustration because participants felt insecure about hitting obstacles. Further, it was frustrating for the participants to sit and turn themselves backwards into an uncomfortable position to scan the area behind the wheelchair.

5.7.6 Perceived Effort

As hypothesized, effort when using the cane alone was significantly higher because participants had to put extra physical effort in scanning of the environment by cane. Further, there was mental effort involved in learning to coordinate both hands while navigating towards the target sound. Mental effort when using the cane is likely to decline as people learn to coordinate both hands (scanning and maneuvering). Further, the physical effort component can be reduced by teaching efficient environment scanning strategies.

5.7.7 Total Workload

As hypothesized, total workload was significantly higher when using the cane alone. When using the cane alone, TLX-PD and TLX-E together were responsible for 47% of TLX-TWL. Further, TLX-MD accounted for 20% and TLX-F contributed 16% of TLX-TWL.

5.8 COMPARING STUDY 1 (FORWARD) AND STUDY 2 (BACKWARD)

5.8.1 Collisions

The forward driving study and backward driving study used different obstacle courses. In the forward study, there were nine obstacles in each obstacle course (see Appendix A.2.1) while in the backward driving study there were five obstacles (see Appendix A.3) in each obstacle course. The numbers of obstacles were reduced in the backward study because participants had trouble navigating the courses with more obstacles when driving backwards. Even with low number of obstacles in the backward driving study, there was no significant difference in the number of collisions in the forward and the backward driving study (Cane: p=0.076 ; DSS: p=0.728 ; Cane&DSS: p=0.780).

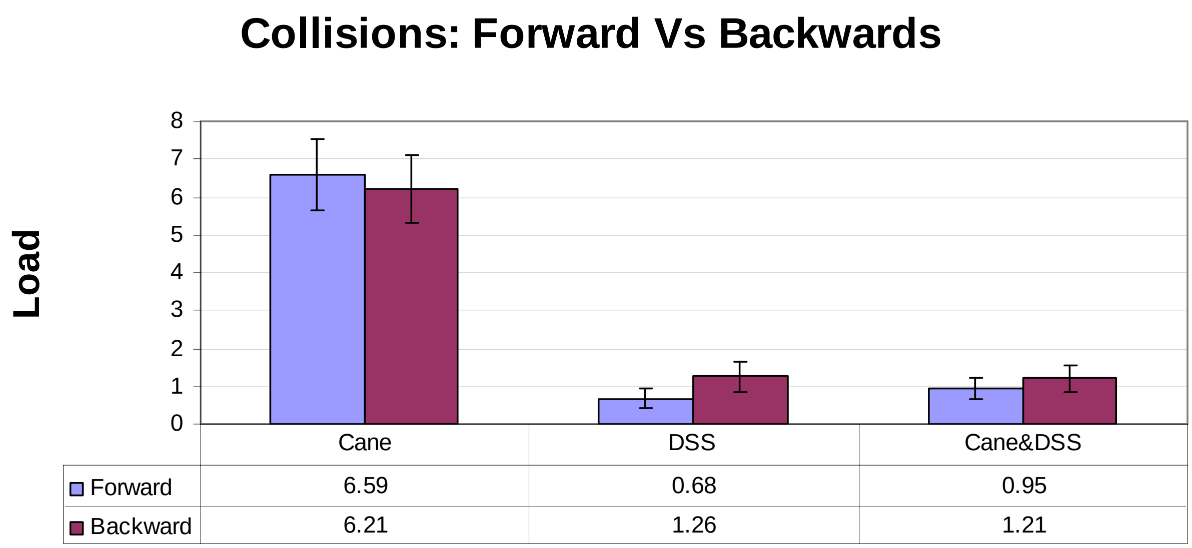
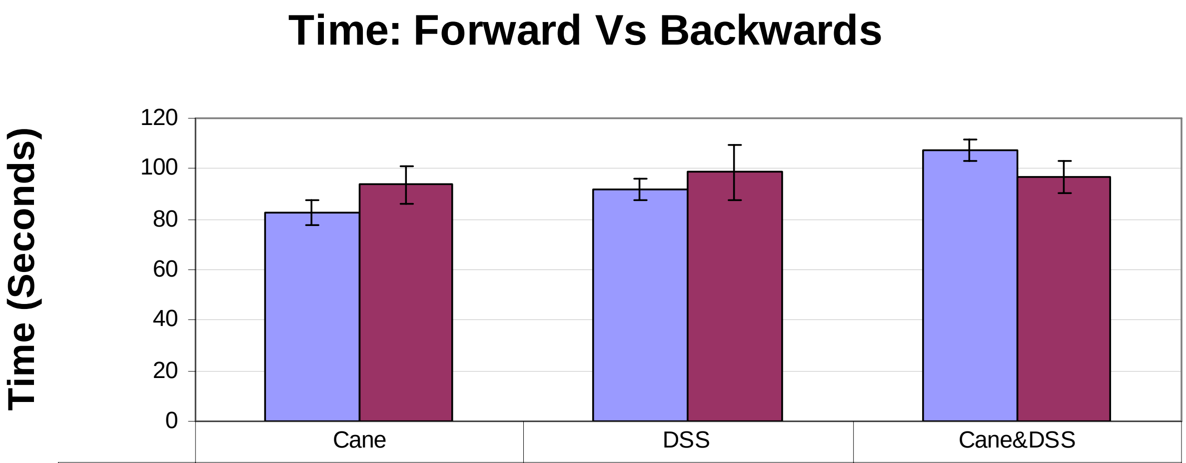


Figure 5-4: Collisions: Forward and Backward

5.8.2 Task completion time

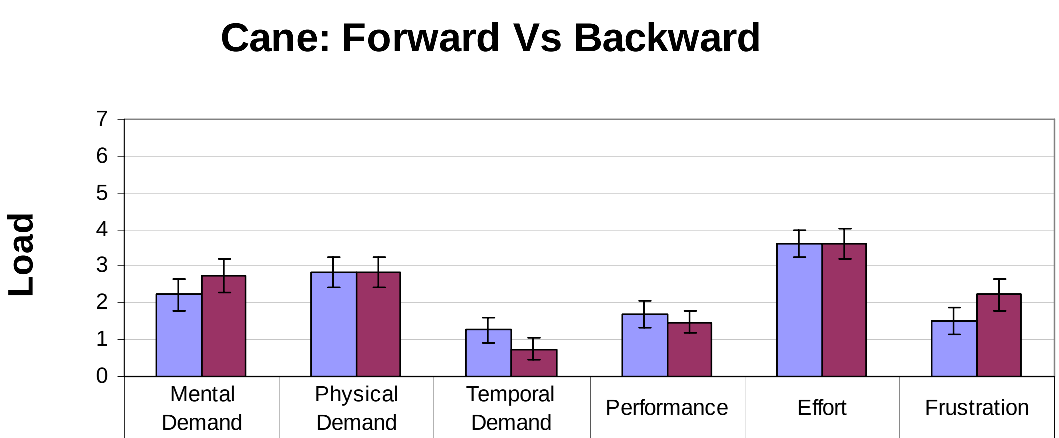
The maximum forward speed of the wheelchair was set at 1.7 MPH, while the maximum backward speed was set at 1.3 MPH. There was no difference in the TCT in the forward and the backward driving study (Cane: $p=0.102$; DSS: $p=0.543$; Cane&DSS: $p=0.202$).



	Cane	DSS	Cane&DSS
Forward	82.67	91.53	107.24
Backward	93.75	98.49	96.81

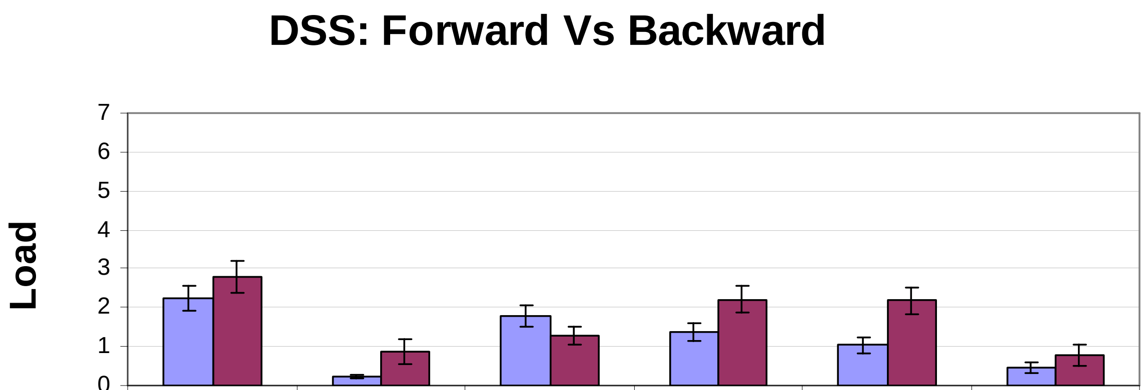
Figure 5-5: Task Completion Time: Forward vs Backward

5.8.3 NASA-TLX



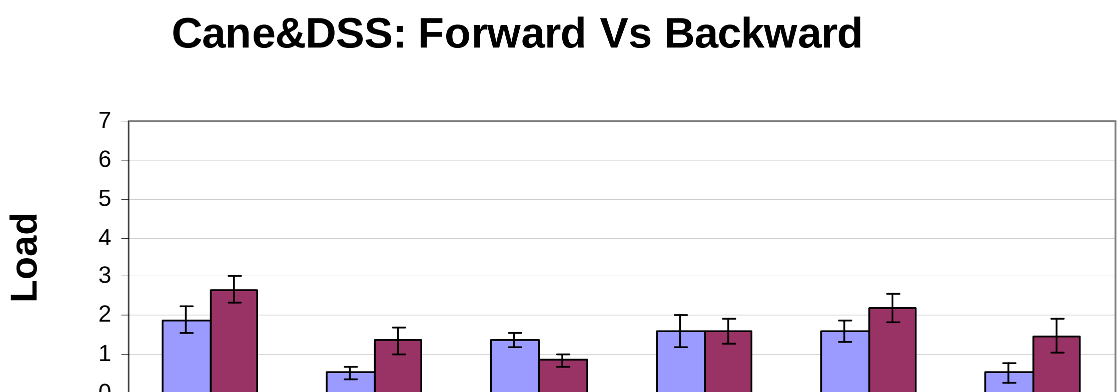
	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration
Forward	2.24	2.84	1.26	1.69	3.62	1.53
Backward	2.75	2.82	0.74	1.47	3.61	2.23

Figure 5-6: Cane: Forward Vs Backward



	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration
Forward	2.22	0.22	1.8	1.38	1.04	0.45
Backward	2.78	0.86	1.29	2.21	2.18	0.76

Figure 5-7: DSS: Forward Vs Backward



	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration
Forward	1.89	0.53	1.37	1.6	1.6	0.53
Backward	2.67	1.36	0.87	1.60	2.18	1.49

Figure 5-8: Cane&DSS Forward vs. Backwards

5.8.3.1 Mental Demand

Participants experienced more mental demand in the backward study in comparison to the forward study but this difference was not statistically significant (Cane: p=0.243 ; DSS: p=0.210 ; Cane&DSS: p=0.124).

The reason for more mental demand in the backward study was primarily due to the poor reverse directional stability of the wheelchair due to caster orientation and driving speed. Further, participants found it difficult to localize the sound target when it was in the back, which occasionally made participants to go in the wrong direction.

5.8.3.2 Physical Demand

Even though scanning the area behind the wheelchair with a cane required more physical labor than scanning the area in front of the wheelchair, there was no difference in the physical demand in forward and backward driving conditions when using the cane alone (p=0.968).

Physical demand was significantly more in the backward driving study when using the DSS alone and the DSS along with the cane (DSS: p=0.005; Cane&DSS: p=0.007). Participants had to make more joystick maneuvers to move around an obstacle when driving backwards using the DSS, this may have added the additional physical demand participants felt when driving backwards.

5.8.3.3 Effort

There was no difference in the perceived effort in these two conditions when using the cane alone and along with the DSS (Cane: p=0.981; Cane&DSS: p=0.240). Surprisingly, the perceived effort in the backward driving was significantly higher than forwards driving when using the DSS alone (p=0.001). Participants had to make more joystick maneuvers to move around an obstacle when driving backwards because of the DSS's inability to navigate the narrow spaces, this may have added the additional effort participants felt when driving backwards.

5.8.3.4 Frustration

Participants felt more frustration in the backward driving study but there was no significant difference in the experienced frustration level when using the cane or the DSS alone (Cane: p=0.151 ; DSS: p=0.507). Participants in the backwards study experience significantly more frustration level when driving backwards using the cane along with the DSS (p=0.025). Maintaining the coordination between the cane and the DSS in the backward driving study was more frustrating for the participants.

5.8.3.5 TLX-TWL

Participants felt more TLX-TWL in the backward driving study but there was no significant difference in the experienced frustration level when using the cane alone or with the DSS (Cane: p=0.572 ; Cane&DSS: p=0.058). Participants in the backwards study experience significantly more TLX-TWL when driving backwards using the DSS alone (p=0.008). Inability of the DSS to cross the narrow spaces when moving backwards, directional instability of the wheelchair in backward direction and difficulty in localizing the sound source in backward direction made the navigation task more challenging in comparison to the forward driving task and participants experienced more workload. The additional TLX-TWL when driving backwards was contributed by more mental and physical demand, worse performance, more effort, and greater level of frustration.

5.9 CONCLUSIONS

Nearly all hypotheses were supported by the data. The DSS reduced the number of collisions and the severity of collisions without increasing the time required to complete the navigation tasks. The DSS also reduced physical demand, frustration, perceived effort and total workload.

6.0 STUDY 3: ORIENTATION AND MOBILITY (O&M) SPECIALISTS

6.1 INTRODUCTION

The study described in this section employed able-bodied orientation and mobility (O&M) experts wearing blindfolds to simulate complete blindness. O&M experts provide training, conduct assessments, design programs, and provide instructions about the use of assistive mobility devices to people with visual and mobility impairments [62]. O&M experts teach people with visual impairments to maximize the use of their remaining senses, such as localization of sounds and tactile discrimination [62]. As O&M specialists are familiar with the needs and limitations of the intended population of the DSS, it was hoped that their evaluation of the DSS technology would provide insight into the viability of the DSS for people with visual and mobility impairments.

6.2 HYPOTHESES AND SPECIFIC AIMS

The purpose of this study was to determine if the DSS provides effective independent mobility to able bodied O&M specialists when they are simulating the condition of people with visual and mobility impairments.

Specific Aim 1. To evaluate the effectiveness of the DSS versus cane on a forward moving navigation task based on quantitative measures such as number of collisions and task completion time. Following hypotheses were associated with the specific aim 1:

Hypothesis Q1. O&M specialists will have fewer collisions when using the DSS than when using a cane.

Hypothesis Q2. The average time of completion for a task will be greater when using the DSS in comparison to a cane.

Specific Aim 2. To evaluate the subjective workload associated with the use of the DSS on a navigation task and compare it with the subjective workload associated with the use of a cane on the similar navigation task. Following hypotheses were associated with the specific aim 2:

Hypothesis S1. Perceived physical demand in a given navigation task will be lower when using the DSS than when using a cane.

Hypothesis S2. Perceived mental demand will be higher when using the DSS than when using a cane.

Hypothesis S3. Frustration when using the DSS will be lower than when using a cane.

Hypothesis S4. Perceived effort when using the DSS will be lower than when using a cane.

Hypothesis S5. TWL when using the DSS will be lower than when using a cane.

Specific Aim 3. To evaluate the performance and robustness of the DSS based on the objective measures (e.g. number of collisions, task completion time, number of system resets required during the trials, errors in the architecture) and subjective measures (e.g. workload, users' recommendation, investigators observation of users' performance) and, based on the results, determine the changes required in the hardware (e.g., electronics and sensor housings, mountings), software (e.g., slow threshold, stop threshold) and user interface (e.g., auditory feedback, visual feedback).

6.3 SUBJECTS

6.3.1 Recruitment

The study protocol was approved by the Institutional Review Board (IRB) of the University of Pittsburgh on March 10, 2008. A further modification in the study protocol was accepted by the IRB on September 3, 2008, after which the recruitment process was begun. Eight Orientation and Mobility (O&M) experts were recruited from the organizations serving people with visual impairments in Pittsburgh and nearby regions.

6.3.2 Inclusion / exclusion

Inclusion criteria for participants were as follows:

- Be older than 21 years of age
- Be a certified Orientation and Mobility (O&M) specialist for people with visual impairments.
- Be able to read, write and understand instructions in English.
- Have normal hearing ability

- Be available to finish the trials in one or two sessions within a week

Exclusion criteria for participants were as follows:

- Do not have experience using a wheelchair in everyday life
- Do not have any medical condition that would interfere with driving a wheelchair while blindfolded, such as nausea or dizziness.

6.3.3 Demographics

Eight O&M experts (2 Males, 6 Females) were recruited for this study. The mean age of participants was 49.75 years (SD 12.60 y). Participants had 19.37 years (SD 10.62 y) of experience in orientation and mobility services for people with visual impairments. Most of the participants in this study had prior experience with teaching people with visual and mobility impairments to drive wheeled mobility devices (e.g. manual and powered wheelchair).

6.4 METHODS

6.4.1 Informed Consent

Prior to participating in the study, each participant read the Informed Consent Form. Once each participant indicated that the form had been read and understood, and agreed to participate, the informed consent form was signed. A copy of the informed consent form was given to the participants upon completion of the experiment.

6.4.2 Seating and Positioning

Depending upon participants' requirements, the seating and positioning of the wheelchair was adjusted by the investigator. For example, the wheelchair joystick was mounted on the right or the left side of the wheelchair, depending upon whether the participant was left-handed or right-handed.

6.4.3 Training

Participants completed the same training activities as participants in Study 1 (see Section 4.4.2.3).

6.4.4 Protocol

The same protocol used in Study 1 (see Section 4.4.2.4) was followed but in each condition there were 6 trials instead of 3 as in Study 1. Six obstacle courses in each condition were randomly chosen from courses shown in Appendix A.2.1 and Appendix A.2.2.

6.4.5 Data Collection

All of the measures used in Study 1 (see Section 4.4.2.5) were collected.

6.5 DATA ANALYSIS

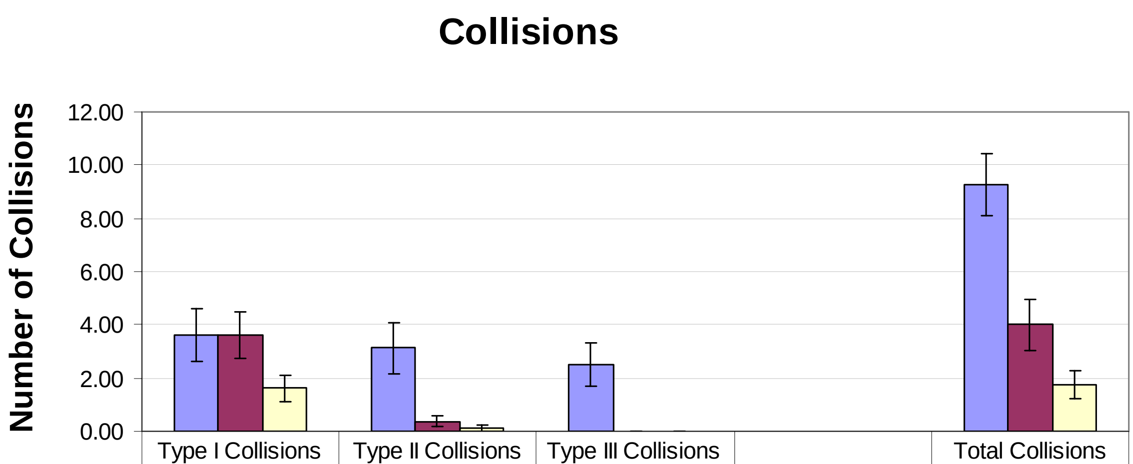
The same approach to statistical analysis used in Study 1 (see Section 4.5) was used. Table 6-1 was used to determine the normality of the dependent variables in three experimental conditions.

Table 6-1: Data Normality (O&M Specialists)

Conditions / Variables	Cane		DSS		Cane&DSS	
	Shapiro-Wilk	Normality	Shapiro-Wilk	Normality	Shapiro-Wilk	Normality
Type I Collisions (NCT-I)	0.358	**Yes**	0.631	**Yes**	0.557	**Yes**
Type II Collisions (NCT-II)	0.496	**Yes**	0.0001	No	0.0001	No
Type III Collisions (NCT-III)	0.114	**Yes**	0.0001	No	0.0001	No
Total Collisions (NCT-T)	0.467	**Yes**	0.929	**Yes**	0.428	**Yes**
Trial Completion Time (TCT)	0.083	**Yes**	0.232	**Yes**	0.507	**Yes**
Mental Demand (TLX-MD)	0.568	**Yes**	0.875	**Yes**	0.519	**Yes**
Physical Demand (TLX-PD)	0.717	**Yes**	0.0001	No	0.085	**Yes**
Temporal Demand (TLX-TD)	0.008	No	0.703	**Yes**	0.545	**Yes**
Performance (TLX-P)	0.500	**Yes**	0.815	**Yes**	0.273	**Yes**
Effort (TLX-E)	0.632	**Yes**	0.008	No	0.184	**Yes**
Frustration (TLX-F)	0.014	No	0.027	No	0.0001	No
Total Workload (TLX-TWL)	0.497	**Yes**	0.744	**Yes**	0.158	**Yes**

6.6 RESULTS

6.6.1 Collisions



	Type I Collisions	Type II Collisions	Type III Collisions		Total Collisions
Cane	3.63	3.13	2.50		9.25
DSS	3.63	0.38	0.00		4.00
Cane&DSS	1.63	0.13	0.00		1.75

Figure 6-1: Moving Forward Collisions (O&M Specialists)

6.6.1.1 Number of Type I Collisions per Trial

As shown in Table 6-2, the Number of Type I Collisions per Trial (NCT-I) under the Cane condition had a mean of 3.63 (±2.77). NCT-I under the DSS condition had a mean of 3.63 (±2.45). The lowest NCT-I occurred under the Cane&DSS condition, with a mean of 1.63 (±1.41). NCT-I was normally distributed (Cane: p=0.358; DSS: p=0.631; DSS+Cane: p=0.557).

A significant difference existed between conditions ($F[2, 14]=3.862$, $p=0.046$). NCT-I was lower under Cane&DSS than under the DSS condition and this difference was statistically significant ($p=0.006$). There was not a significant difference in NCT-I under the Cane&DSS and the Cane condition ($p=0.189$).

Table 6-2. Number of Type I Collisions per Trial (NCT-I)

Condition	Mean (n = 8)	Range
Cane	3.63(±2.77)	[0, 8]
DSS	3.63 (±2.45)	[0, 8]
Cane&DSS	1.63 (±1.41)	[0, 4]

6.6.1.2 Number of Type II Collisions per Trial

As shown in Table 6-3, the Number of Type II Collisions per Trial (NCT-II) was greatest under the Cane condition with a mean of 3.13 (±2.75) per trial. The second largest NCT-II occurred under the DSS condition with a mean of 0.38 (±0.52). The lowest NCT-II occurred under the Cane&DSS condition with a mean of 0.13 (±0.35). NCT-II was not normally distributed (Cane: $p=0.496$; DSS: $p=0.0001$; DSS+Cane: $p=0.0001$).

A significant difference existed between conditions (χ^2 (2 , N = 8) = 10.640, $p=0.005$). Participants had significantly more NCT-II under the Cane condition than under the DSS condition (Z=2.198, $p=0.028$) and the Cane&DSS condition (Z=2.375, $p=0.018$). There was not a significant difference in NCT-II between the DSS and Cane&DSS conditions (Z=-1.414, $p=0.157$).

Table 6-3. Number of Type II Collisions per Trial (NCT-II)

Condition	Mean (n = 8)	Range
Cane	3.13 (±2.75)	[0, 8]
DSS	0.38 (±0.52)	[0, 1]
Cane&DSS	0.13 (±0.35)	[0, 1]

6.6.1.3 Number of Type III Collisions per Trial

As shown in Table 6-3, the Number of Type III Collisions per Trial had a mean of 2.50 (±2.33) under the Cane condition, but there were no Type III collisions under either the DSS or Cane&DSS conditions. NCT-III was not normally distributed (Cane: p=0.114; DSS: p=0.0001; Cane&DSS: p=0.0001).

A significant difference existed between conditions ($\chi^2(2 , N = 8) = 10.00$, p=0.007). Participants had significantly greater NCT-III under the Cane condition than under the Cane&DSS condition (Z=2.060, p=0.039) and the DSS condition (Z=2.060, p=0.039).

Table 6-4. Number of Type III Collisions per Trial (NCT-T)

Condition	Mean (n = 8)	Range
Cane	2.50 (±2.33)	[0, 6]
DSS	0	[0, 0]
Cane&DSS	0	[0, 0]

6.6.1.4 Total Collisions

As shown in Table 6-5, the Cane condition had the greatest Total Number of Collisions per Trial (NCT-T) with a mean of 9.25 (±3.28) The DSS condition had the second greatest NCT-T, with a mean of 4.0 (±2.73). The Cane&DSS condition had the lowest NCT-T, with a mean of 1.75

(±1.49). NCT-T was normally distributed (Cane: p=0.467; DSS: p=0.929; DSS+Cane: p=0.428).

A significant difference existed among driving conditions (F[1.134 , 7.938]=21.925, p=0.001). Participants had significantly greater NCT-T under the Cane condition than under the DSS condition (p=0.032) and the Cane&DSS condition (p=0.001). In addition, participants had significantly greater NCT-T under the DSS condition than under the Cane&DSS condition (p=0.011).

Table 6-5. Number of Total Collisions per Trial (NCT-T)

Condition	Mean (n = 8)	Range
Cane	9.25 (±3.28)	[5, 14]
DSS	4.0 (±2.73)	[0, 9]
Cane&DSS	1.75 (±1.49)	[0, 4]

6.6.2 Task Completion Time

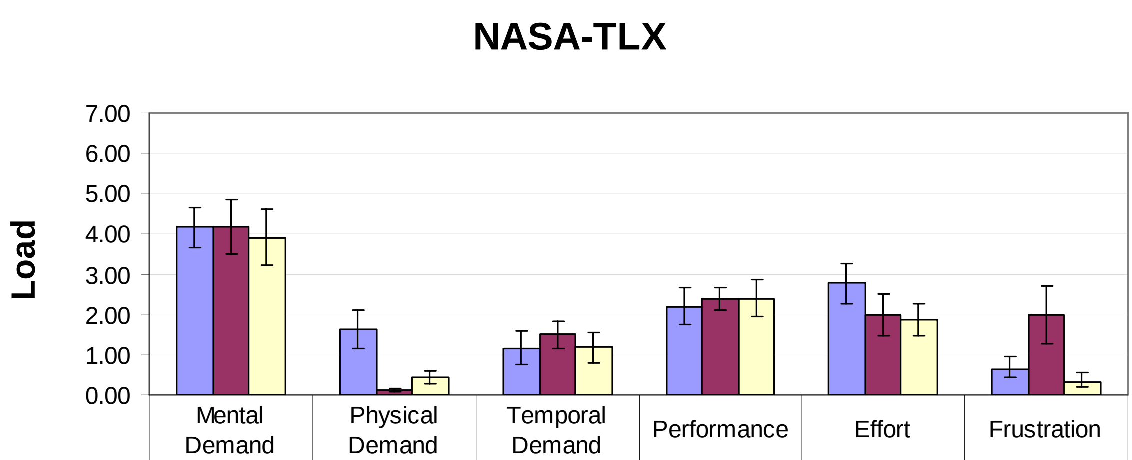
As shown in Table 6-6, mean Task Completion Time (TCT) was lowest under the Cane condition at 58.19 (±18.15) seconds. TCT was 104.29 (±17.34) seconds under the DSS condition and was 105.52 (±21.47) seconds under the Cane&DSS condition. TCT was normally distributed under all three conditions (Cane: p=0.083; DSS: p=0.232; Cane&DSS: p=0.507).

There was a statistically significant difference across conditions (F[2 , 14]=22.364, p<0.0001). TCT under the Cane condition was significantly lower than under the DSS condition (p=0.002) and the Cane&DSS condition (p=0.003). The difference in TCT under the DSS condition and the Cane&DSS condition was not statistically significant.

Table 6-6. Task Completion Time

Condition	Mean (n = 8)	Range
Cane	58.19 (±18.15)	[39.50, 97.83]
DSS	104.29 (±17.34)	[87.33, 138.33]
Cane&DSS	105.52 (±21.47)	[71.83, 130.83]

6.6.3 National Air and Space Administration – Task Load Index



	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration
Cane	4.17	1.64	1.16	2.20	2.78	0.65
DSS	4.18	0.10	1.51	2.38	1.98	1.98
Cane&DSS	3.91	0.43	1.18	2.41	1.87	0.33

Figure 6-2: NASA-TLX (O&M Specialists)

6.6.3.1 Mental Demand

As shown in Table 6-7, TLX-MD was lowest under the Cane&DSS condition with a mean of 3.91 (±1.99). TLX-MD had a mean of 4.17 (±1.42) under the Cane condition and a mean of 4.18

(±1.93) under the DSS condition. TLX-MD was normally distributed under all three conditions (Cane: p=0.568, DSS: p=0.875, and Cane&DSS: p=0.519). There was not a significant difference between conditions (F[2 , 14]=0.319, p=0.732).

Table 6-7: NASA-TLX Mental Demand (TLX-MD)

Condition	Mean (n = 8)	Range
Cane	4.17 (±1.42)	[2.40, 6.67]
DSS	4.18 (±1.93)	[1.07, 6.67]
Cane&DSS	3.91 (±1.99)	[0.60, 6.33]

6.6.3.2 Physical Demand

As shown in Table 6-8, TLX-PD had a mean of 0.10 (±0.19) under the DSS condition, a mean of 0.43 (±0.51) under the Cane&DSS condition and a mean of 1.64 (±1.33) under the Cane condition. TLX-PD was not normally distributed under the DSS condition (p=0.001) but was normally distributed under the Cane and Cane&DSS conditions (Cane: p=0.717, Cane&DSS: p=0.085).

A significant difference existed between conditions (χ^2(2 , N = 8) = 10.138, p=0.006). TLX-PD was significantly greater under the Cane condition than under the DSS condition (Z=2.366, p=0.018) and the Cane&DSS condition (Z=2.240, p=0.025). There was a marginally significant difference in TLX-PD between the DSS and the Cane&DSS conditions (Z=1.782, p=0.075).

Table 6-8: NASA-TLX Physical Demand (TLX-PD)

Condition	Mean (n = 8)	Range
Cane	1.64 (±1.33)	[0, 3.73]
DSS	0.10 (±0.19)	[0, 0.47]
Cane&DSS	0.43 (±0.51)	[0, 1.33]

6.6.3.3 Temporal Demand

As shown in Table 6-9, TLX-TD had a mean of 1.16 (±1.23) under the Cane condition, a mean of 1.18 (±1.07) under the Cane&DSS condition and a mean of 1.51 (±0.95 under the DSS condition. TLX-TD was not normally distributed under the Cane condition (p=0.008) but was normally distributed under DSS and Cane&DSS conditions (DSS: p=0.703, Cane&DSS: p=0.545). There was not a significant difference between conditions. ($\chi^2(2\ , N = 8) = 2.516$, p=0.284).

Table 6-9: NASA-TLX Temporal Demand (TLX-TD)

Condition	Mean (n = 8)	Range
Cane	1.16 (±1.23)	[0, 4.00]
DSS	1.51 (±0.95)	[0, 2.67]
Cane&DSS	1.18 (±1.07)	[0, 3.00]

6.6.3.4 Performance

As shown in Table 6-10, TLX-P had a mean of 2.20 (±1.32) under the Cane condition, a mean of 2.38 (±0.81) under the DSS condition and a mean of 2.41 (±1.34) under the Cane&DSS condition. TLX-P was normally distributed under all experimental conditions (Cane: p=0.500, DSS: p=0.815, Cane&DSS: p=0.273). There was not a significant difference in TLX-P between conditions (F[2 , 14]=0.129, p=0.880).

Table 6-10: NASA-TLX Performance (TLX-P)

Condition	Mean (n = 8)	Range
Cane	2.20 (±1.32)	[0.67, 4.53]
DSS	2.38 (±0.81)	[1.07, 3.47]
Cane&DSS	2.41 (±1.34)	[1.00, 5.00]

6.6.3.5 Perceived Effort

As shown in Table 6-11, TLX-E had a mean of 1.87 (±1.14) under the Cane&DSS condition, a mean of 1.98 (±1.45) under the DSS condition and a mean of 2.78 (±1.39) under the Cane condition. TLX-E was normally distributed under the Cane and the Cane&DSS conditions (Cane: p=0.545, Cane&DSS: p=0.184) but was not normally distributed under the DSS condition (DSS: p=0.008). There was not a significant difference between experimental conditions ($\chi^2(2 , N = 8) = 2.467$, p=0.291).

Table 6-11: NASA-TLX Perceived Effort

Condition	Mean (n = 8)	Range
Cane	2.78 (±1.39)	[0.80, 4.80]
DSS	1.98 (±1.45)	[0.80, 5.33]
Cane&DSS	1.87 (±1.14)	[0.80, 4.00]

6.6.3.6 Frustration

As shown in Table 6-12, TLX-F had a mean of 0.33 (±0.65) under the Cane&DSS condition, a mean of 0.65 (±0.85) under the Cane condition and a mean of 1.98 (±2.01) under the DSS condition. TLX-F was normally distributed under the Cane and the DSS conditions (Cane: p=0.014, DSS: p=0.027) but was not normally distributed under the Cane&DSS condition (Cane&DSS: p=0.0001).

A significant difference existed between conditions (χ^2(2 , N = 8) = 8.240, p=0.016). TLX-F was greater under the DSS condition than under the Cane condition but this difference was not significant (Z=1.690, p=0.091). There was not a significant difference in TLX-F between the Cane and the Cane&DSS conditions (Z=0.944, p=0.345). TLX-F under the Cane&DSS was significantly lower than the DSS condition (Z=2.207, p=0.027).

Table 6-12: NASA-TLX Frustration (TLX-F)

Condition	Mean (n = 8)	Range
Cane	0.65 (±0.85)	[0, 2.00]
DSS	1.98 (±2.01)	[0, 5.00]
Cane&DSS	0.33 (±0.65)	[0, 1.80]

6.6.3.7 Total Workload

As shown in Table 6-13, Total Workload (TLX-TWL) had a mean of 9.45 (±3.60) under the Cane&DSS condition, a mean of 12.12 (±2.90) under the DSS condition and a mean of 12.13 (±3.83) under the Cane condition. TLX-TWL was normally distributed under all three experimental conditions (Cane: p=0.497, DSS: p=0.744, Cane&DSS: p=0.158). There was no significant difference in TLX-TWL between conditions (F[2, 14]=2.938, p=0.086).

Table 6-13: Total Workload

Condition	Mean (n = 8)	Range
Cane	12.13 (±3.83)	[5.73, 16.33]
DSS	12.12 (±2.90)	[8.07, 16.93]
Cane&DSS	9.45 (±3.60)	[5.33, 14.47]

6.7 DISCUSSION

6.7.1 Collisions

As we hypothesized, results from this study indicated that the DSS will promote safe navigation by reducing the number and severity of collisions. Participants had significantly more collisions when using just the cane than when using the cane in combination with the DSS or when using the DSS alone. Most of the collisions that occurred when using the DSS were of very low severity (mainly Type I).

Unlike the able-bodied subjects tested in Study 1, the O&M specialists tested in this study had significant expertise with using a cane. This expertise was primarily responsible for the low number of Type I collisions when using the cane. An interesting result was that the number of collisions when using the cane in combination with the DSS was significantly lower than the number of collisions when using the DSS alone or the cane alone.

6.7.2 Task Completion Time

As hypothesized, TCT was lowest when using the cane alone. However, as shown in Figure 20, this performance was achieved at the expense of hitting significantly more obstacles. The O&M specialists tested in this study had significant expertise with using a cane. This expertise was primarily responsible for the lower task completion time with the cane alone.

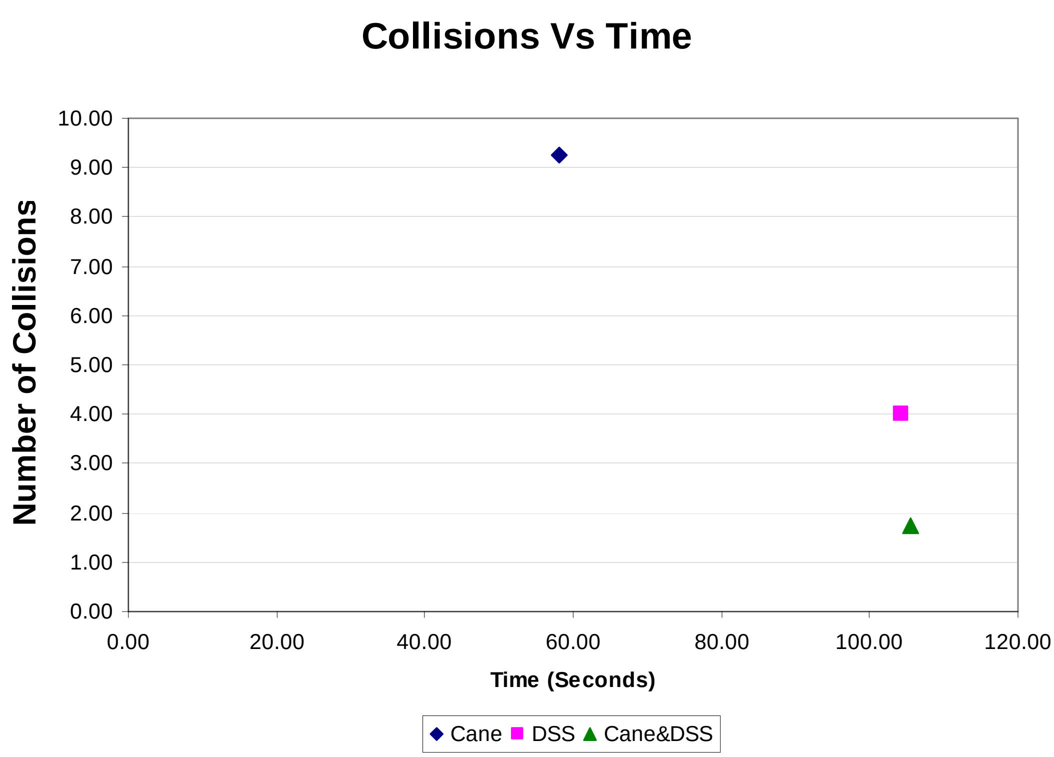


Figure 6-3: Collisions Vs Task Completion Time

6.7.3 Physical Demand

As hypothesized, physical demand was significantly higher when using the cane. It should be noted; however, that physical demand was still low (1.64 on a scale of 0 to 7) under the cane condition so it is unclear whether physical demand was actually problematic.

6.7.4 Mental Demand

The hypothesis that mental demand would be greater when using the cane alone was not supported. There was not a significant difference between conditions. Mental demand was high under all three conditions, however, indicating that subjects experienced significant mental demand. A likely source of mental demand under all conditions was the need to construct and maintain a mental map of the test environment (the target, surrounding obstacles, the position and orientation of the wheelchair).

Mental demand when using the cane alone resulted from the need to coordinate scanning and driving. This was difficult for O&M participants because they normally use their dominant hand for the cane but they had to use their non-dominant hand for scanning while maneuvering the joystick using their dominant hand. Mental demand when using the cane may be reduced by teaching people appropriate scanning techniques while driving the wheelchair. Mental demand would also be expected to decrease over time as they learn to coordinate scanning and driving.

Mental demand when using DSS was caused when participants had to estimate the position and sizes of obstacles based on auditory feedback from the wheelchair and then use this information to maneuver the wheelchair around obstacles and move towards the sound target. In addition, crosstalk between ultrasound sensors could cause the wheelchair to act in ways that confused participants requiring them to work extra hard mentally to reach to the target.

Mental demand when using the DSS may be reduced by making the auditory feedback more informative by encoding information about the distance of the obstacle from the wheelchair, which could help people to steer the wheelchair away from obstacles. In addition, reducing or eliminating sensor crosstalk will allow the wheelchair to behave more intuitively and further reduce mental demand.

6.7.5 Frustration

The hypothesis that frustration would be significantly higher when using the cane alone was not supported. In fact, frustration was higher under the DSS-only condition. It should be noted, however, that frustration was still low (1.98 on a scale of 0 to 7) under the DSS condition so it is unclear whether frustration was actually problematic.

6.7.6 Perceived Effort

The hypothesis that perceived effort would be greater when using the cane alone was not supported. There was not a significant difference between conditions. In addition, perceived effort was not particularly high under any condition.

6.7.7 Total Workload

The hypothesis that total workload would be greater when using the cane alone was not supported. There was not a significant difference between conditions.

6.8 COMPARING STUDIES 1 AND 3

Like the able-bodied participants in Studies 1 and 2, the O&M Specialists who participated in Study 3 were not experienced wheelchair users and were not experienced at navigating without sight. Unlike the able-bodied participants from Studies 1 and 2, however, these participants were skilled cane users and were at least familiar with the navigation strategies used by people with visual impairments.

The O&M Specialists had more collisions than able-bodied subjects when using the DSS alone but this difference was not statistically significant (p=0.065). Task completion time for O&M Specialists was consistent with able-bodied subjects when DSS was active (p=0.113), but was significantly faster when using the cane alone (p=0.008).O&M Specialists reported significantly greater mental demand under all conditions (Cane: p=0.016 ; DSS: p=0.007 ; Cane&DSS: p=0.007) As one would expect, O&M Specialists reported much lower physical demand (p=0.110) and perceived effort (p= 0.208) than able-bodied subjects when using the cane but these differences were not statistically significant.There were definite differences in the frustration experienced by each group. O&M Specialists were most frustrated (by a large margin) when using DSS alone (DSS: p=0.006). Able-bodied participants, on the other hand, were most frustrated (again by a large margin) when using the cane alone (p=0.157). Able-bodied subjects and O&M Specialists reported very similar total workload scores for using the cane alone (p=0.528). However, Able-bodied subjects reported much lower total workload when using DSS alone (p=0.0001). There was less difference between groups for the combined cane and DSS condition (p=0.235).

6.9 CONCLUSIONS

Several of the hypotheses were not supported; many results did not reach on the significance level because of the small subject sample size. O&M participants did not experience any significant difference in the mental demand, perceived effort, frustration or total workload. Participants felt less physical demand when driving the wheelchair while receiving navigation assistance from the DSS. The results from this study were consistent with Study 1 in that use of the DSS reduced collisions of medium and high severity, but this increased safety is achieved at the expense of increased task completion time.

7.0 STUDY 4: PARTICIPANTS WITH VISUAL IMPAIRMENT

7.1 INTRODUCTION

Study 4 employed people who had visual impairments but did not have mobility impairments. People with visual impairments can evaluate the merits of the DSS for people with both visual and mobility impairments because both populations carry the similar skill set of cane usage, sound localization, and geographic reasoning. Further, both experience similar challenges in performing ADLs.

7.2 HYPOTHESES AND SPECIFIC AIMS

The purpose of this study was to determine if the DSS provides effective independent mobility to participants with visual impairments when they are simulating the condition of people with visual and mobility impairments.

Specific Aim 1. To evaluate the effectiveness of the DSS versus cane on a forward moving navigation task based on quantitative measures such as number of collisions and task completion time. Following hypotheses were associated with the specific aim 1:

Hypothesis Q1. Participants will have fewer collisions when using the DSS than when using a cane.

Hypothesis Q2. The average time of completion for a task will be greater when using the DSS in comparison to a cane.

Specific Aim 2. To evaluate the subjective workload associated with the use of the DSS on a navigation task and compare it with the subjective workload associated with the use of a cane on the similar navigation task. Following hypotheses were associated with the specific aim 2:

Hypothesis S1. Perceived physical demand in a given navigation task will be lower when using the DSS than when using a cane.

Hypothesis S2. Perceived mental demand will be higher when using the DSS than when using a cane.

Hypothesis S3. Frustration when using the DSS will be lower than when using a cane.

Hypothesis S4. Perceived effort when using the DSS will be lower than when using a cane.

Hypothesis S5. TWL when using the DSS will be lower than when using a cane.

Specific Aim 3. To evaluate the performance and robustness of the DSS based on the objective measures (e.g. number of collisions, task completion time, number of system resets required during the trials, errors in the architecture) and subjective measures (e.g. workload, users' recommendation, investigators observation of users' performance) and, based on the results, determine the changes required in the hardware (e.g., electronics and sensor housings, mountings), software (e.g., slow threshold, stop threshold) and user interface (e.g., auditory feedback, visual feedback).

7.3 SUBJECTS

7.3.1 Recruitment

The study protocol was approved by the Institutional Review Board (IRB) of the University of Pittsburgh on March 10, 2008. A further modification in the study protocol was accepted by the IRB on September 3, 2008, after which the recruitment process was begun. Seven individuals with visual impairments were recruited from the organizations serving people with visual impairments in Pittsburgh and nearby regions.

7.3.2 Inclusion / exclusion

Inclusion criteria for the participants were as follows:

- Be older than 21 years of age
- Be legally blind
- Have normal hearing ability
- Be available to finish the trials in one or two sessions within a week

Exclusion criteria for participants were as follows:

- Do not have experience using a wheelchair in everyday life
- Do not have any medical condition that would interfere with driving a wheelchair, such as nausea or dizziness.

7.3.3 Demographics

Seven subjects with visual impairments (4 Males, 3 Females) were recruited for this study. Mean age of participants was 53.71 years (SD 16.41 y). Nearly all participants had congenital visual impairment. Five participants in this study had prior experience with wheeled mobility devices for a short period of time, mostly when they were unable to walk due to a temporary medical condition (e.g. fractured bone, surgery). None of the participants was using a wheeled mobility device at the time of their participation in the study.

7.4 METHODS

7.4.1 Informed Consent

Prior to participating in the study, the investigator read and explained each section of the Informed Consent Form to each participant. Once each participant indicated that the form had been understood, and agreed to participate, the informed consent form was signed. A copy of the informed consent form was given to the participants upon completion of the experiment.

7.4.2 Seating and Positioning

Depending upon participants' requirements, the seating and positioning of the wheelchair was adjusted by the investigator. For example, the wheelchair joystick was mounted on the right or the left side of the wheelchair, depending upon whether the participant was left-handed or right-handed.

7.4.3 Training

Participants completed the same training activities as participants in Study 1 (see Section 4.4.2.3).

7.4.4 Protocol

The same protocol used in Study 1 (see Section 4.4.2.4) was followed but in each condition there were 6 trials instead of 3 as in Study 1. Order of experimental conditions and obstacle courses were randomized for each participant. Six obstacle courses in each condition were randomly chosen from courses shown in Appendix A.2.1 and Appendix A.2.2 and no two obstacle courses in a condition were same.

7.4.5 Data collection

All of the measures used in Study 3 (see Section 6.4.5) were collected.

7.5 DATA ANALYSIS

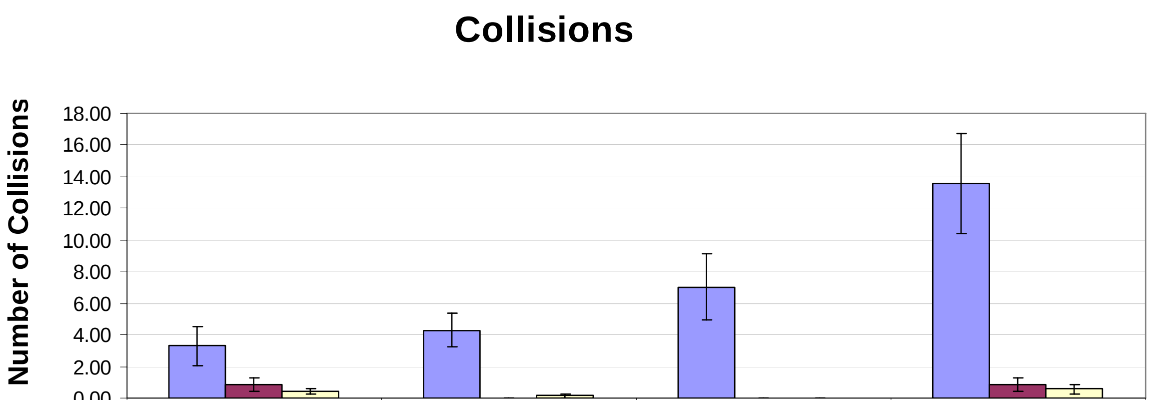
The same approach to statistical analysis used in Study 1 (see Section 4.5) was used. Table 7-1 was used to determine the normality of the dependent variables in three experimental conditions.

Table 7-1: Data Normality (Visually Impaired Participants)

Conditions / Variables	Cane		DSS		Cane&DSS	
	Shapiro-Wilk	Normality	Shapiro-Wilk	Normality	Shapiro-Wilk	Normality
Type I Collision (NCT-I)	0.009	No	0.026	**Yes**	0.001	No
Type II Collision (NCT-II)	0.055	**Yes**	0.0001	No	0.0001	No
Type III Collision (NCT-III)	0.532	**Yes**	0.0001	No	0.0001	No
Total Collisions (NCT-T)	0.176	**Yes**	0.026	**Yes**	0.20	**Yes**
Trial Completion Time (TCT)	0.897	**Yes**	0.284	**Yes**	0.037	**Yes**
Mental Demand (TLX-MD)	0.070	**Yes**	0.364	**Yes**	0.030	**Yes**
Physical Demand (TLX-PD)	0.253	**Yes**	0.006	No	0.082	**Yes**
Temporal Demand (TLX-TD)	0.056	**Yes**	0.0001	No	0.078	**Yes**
Performance (TLX-P)	0.384	**Yes**	0.377	**Yes**	0.218	**Yes**
Effort (TLX-E)	0.474	**Yes**	0.070	**Yes**	0.001	**No**
Frustration (TLX-F)	0.085	**Yes**	0.0001	No	0.053	**Yes**
Total Workload (TLX-TWL)	0.262	**Yes**	0.197	**Yes**	0.272	**Yes**
MPT	0.628	**Yes**	0.039	**Yes**	0.136	**Yes**

7.6 RESULTS

7.6.1 Collisions



	Type I Collisions	Type II Collisions	Type III Collisions	Total Collisions
Cane	3.29	4.29	7.00	13.57
DSS	0.86	0.00	0.00	0.86
Cane&DSS	0.43	0.14	0.00	0.57

Figure 7-1: Moving Forward Collisions (Subjects with Visual Impairment)

7.6.1.1 Type I Collisions

As shown in Table 7-2, The Number of Type I Collisions (NCT-I) under the Cane condition had a mean of 3.29 (±3.30) per trial, a mean of 0.86 (±1.07) under the DSS condition and a mean of 0.86 (±1.07) under the Cane&DSS condition. NCT-I was not normally distributed (Cane: p=0.009; DSS: p=0.026; DSS+Cane: p=0.001).

A significant difference existed between conditions (χ^2[2 , 7]=9.364, p=0.009). The difference in NCT-I under the DSS condition and the Cane condition was not significant (Z=1.725, p= 0.084). The difference in NCT-I under the DSS condition and the Cane&DSS condition was not significant (Z=1.342, p=0.180). NCT-I was significantly lower under the Cane&DSS condition than under the Cane condition (Z= 2.546, p=0.014).

Table 7-2. Number of Type I Collisions per Trial (NCT-I)

Condition	Mean (n = 7)	Range
Cane	3.29(±3.30)	[1, 9]
DSS	0.86 (±1.07)	[0, 3]
Cane&DSS	0.43 (±0.535)	[0, 1]

7.6.1.2 Type II Collisions

As shown in Table 7-3, the Number of Type II Collisions per Trial (NCT-II) was greatest under the Cane condition with a mean of 4.29 (±2.87). The second largest NCT-II occurred under the Cane&DSS condition with a mean of 0.14 (±0.38). There were no Type II collisions with the DSS. NCT-II was not normally distributed (Cane: p=0.055; DSS: p=0.0001; DSS+Cane: p=0.0001).

A significant difference existed between conditions (χ^2 (2 , N = 7) = 13.445, p=0.001). Participants had significantly greater NCT-II under the Cane condition than under the DSS condition (Z=2.375, p=0.018) and the Cane&DSS condition (Z=2.388, p=0.017). There was not a significant difference in NCT-II between the DSS and Cane&DSS conditions (Z=-1.00, p=0.317).

Table 7-3. Number of Type II Collisions per Trial (NCT-II)

Condition	Mean (n = 7)	Range
Cane	4.29 (±2.87)	[2, 10]
DSS	0.0 (±0.0)	[0, 0]
Cane&DSS	0.14 (±0.38)	[0, 1]

7.6.1.3 Type III Collisions

As shown in Table 7-4, The Number of Type III Collisions per Trial (NCT-III) had a mean of 7.00 (±2.33) under the Cane condition, but there were no Type III Collisions under either the DSS or Cane&DSS conditions. NCT-III was not normally distributed (Cane: p=0.532; DSS: p=0.0001; Cane&DSS: p=0.0001).

A significant difference existed between conditions ($\chi^2(2\ ,\ N = 7) = 12.00$, p=0.002). Participants had significantly greater NCT-III under the Cane condition than under the Cane&DSS condition (Z=2.201, p=0.028) and the DSS condition (Z=2.201, p=0.028).

Table 7-4. Number of Type III Collisions per Trial (NCT-III)

Condition	Mean (n = 7)	Range
Cane	7.00 (±2.33)	[0, 14]
DSS	0	[0, 0]
Cane&DSS	0	[0, 0]

7.6.1.4 Total Collisions:

As shown in Table 7-5, the Cane condition had the greatest Total Number of Collisions per Trial (NCT-T) with a mean of 13.57 (±8.30) The DSS condition had the second most NCT-T, with a mean of 0.86 (±1.07). The Cane&DSS condition had the lowest NCT-T, with a mean of 0.57 (±0.79). NCT-T was normally distributed (Cane: p=0.467; DSS: p=0.929; DSS+Cane: p=0.428).

A significant difference existed between conditions (F[1.014 , 6.086]=16.719, p=0.001). Participants had significantly greater NCT-T under the Cane condition than under the DSS condition (p=0.023) and the Cane&DSS condition (p=0.016). There was no difference in NCT-T between the DSS and Cane&DSS conditions (p=1.00).

Table 7-5. Total Number of Collisions per Trial (NCT-T)

Condition	Mean (n = 7)	Range
Cane	13.57 (±8.30)	[5, 26]
DSS	0.86 (±1.07)	[0, 3]
Cane&DSS	0.57 (±0.79)	[0, 2]

7.6.2 Task Completion Time

As shown in Table 7-6, mean Task Completion Time (TCT) was lowest under the Cane condition at 65.71 (±23.08) seconds. TCT was 80.88 (±13.34) seconds under the DSS condition and was 100.02 (±15.23) seconds under the Cane&DSS condition. TCT was normally distributed under all three conditions (Cane: p=0.897; DSS: p=0.284; Cane&DSS: p=0.037).

There was a statistically significant difference between conditions (F[2 , 12]=7.969, p<0.006). TCT under the Cane condition was lower than under the Cane&DSS condition and this difference was statistically significant (p=0.001). TCT under the Cane condition was lower than under the DSS condition, but this difference was not significant (p=0.182). TCT under DSS was lower than under the Cane&DSS condition, but this difference was not statistically significant (p=0.701).

Table 7-6. Task Completion Time (TCT)

Condition	Mean (n = 7)	Range
Cane	65.71 (±23.08)	[36.17, 101.83]
DSS	80.88 (±13.34)	[65.83, 101.67]
Cane&DSS	100.02 (±15.23)	[86.67, 124.17]

7.6.3 National Air and Space Administration – Task Load Index

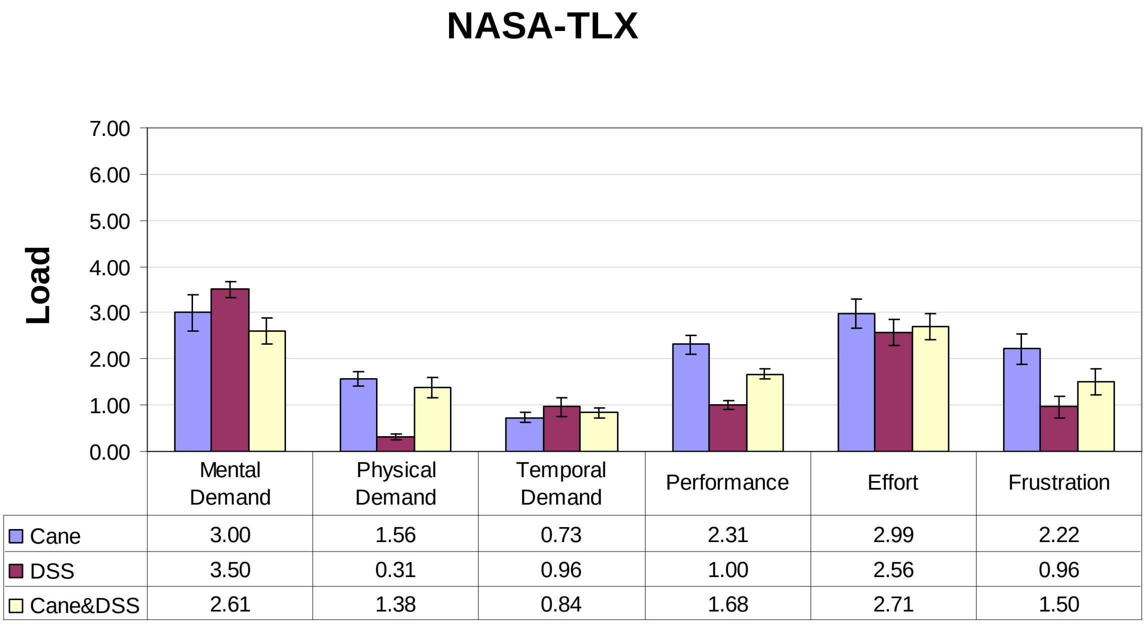


Figure 7-2: NASA-TLX (Participants with Visual Impairments)

7.6.3.1 Mental Demand

As shown in Table 7-7, TLX-MD was lowest under the Cane&DSS condition at 2.61 (±2.04). TLX-MD was 3.00 (±2.69) under the Cane condition and was 3.50 (±1.20) under the DSS condition. TLX-MD was normally distributed under all three conditions (Cane: p=0.070; DSS:

p=0.364; and Cane&DSS: *p*=0.030). There was not a significant difference in TLX-MD between conditions ($F[2, 12]=0.761$, $p=0.489$).

Table 7-7: NASA-TLX Mental Demand (TLX-MD)

Condition	Mean (n = 7)	Range
Cane	3.00 (±2.69)	[0.0, 6.00]
DSS	3.50 (±1.20)	[1.87, 5.00]
Cane&DSS	2.61 (±2.04)	[0.93, 5.60]

7.6.3.2 Physical Demand

As shown in Table 7-8, TLX-PD was lowest under the DSS condition at 0.10 (±0.19). TLX-PD had a mean of 0.43 (±0.51) under the Cane&DSS condition and a mean of 1.64 (±1.33) under the Cane condition. TLX-PD was not normally distributed under the DSS condition ($p=0.006$) but was normally distributed under the Cane and Cane&DSS conditions (Cane: $p=0.253$, Cane&DSS: $p=0.082$).

A significant difference existed between conditions ($\chi^2(2, N = 7) = 6.741$, $p=0.034$). TLX-PD was significantly greater under the Cane condition than under the DSS condition (Z=2.375, $p=0.018$). There was not a significant difference in TLX-PD between the Cane and Cane&DSS conditions (Z=0.169, $p=0.866$) or the DSS and the Cane&DSS conditions (Z=1.577, $p=0.115$).

Table 7-8: NASA-TLX Physical Demand (TLX-PD)

Condition	Mean (n = 7)	Range
Cane	1.56 (±1.12)	[0.33, 3.00]
DSS	0.31 (±0.51)	[0.0, 1.33]
Cane&DSS	1.38 (±1.52)	[0.0, 4.00]

7.6.3.3 Temporal Demand

As shown in Table 7-9, TLX-TD was lowest under the Cane condition with a mean of 0.73 (±0.72). TLX-TD had a mean of 0.84 (±0.82) under the Cane&DSS condition and a mean of 0.96 (±1.47) under the DSS condition. TLX-TD was not normally distributed under the DSS condition (p=0.0001) but was normally distributed under Cane and Cane&DSS conditions (Cane: p=0.056; Cane&DSS: p=0.078). There was not a significant difference between conditions (χ^2(2 , N = 7) = 0.333, p=0.846).

Table 7-9: NASA-TLX Temporal Demand (TLX-TD)

Condition	Mean (n = 7)	Range
Cane	0.73 (±0.72)	[0, 1.60]
DSS	0.96 (±1.47)	[0.13, 4.27]
Cane&DSS	0.84 (±0.82)	[0, 2.00]

7.6.3.4 Performance

As shown in Table 7-10, TLX-P was highest under the Cane condition at 2.31 (±1.37). TLX-P had a mean of 1.68 (±0.75) under the Cane&DSS condition and a mean of 1.00 (±0.60) under the DSS condition. TLX-P was normally distributed under all experimental conditions (Cane: p=0.384, DSS: p=0.377, Cane&DSS: p=0.218). There was not a significant difference in TLX-P between conditions (F[2 , 12]=3.202, p=0.077).

Table 7-10: NASA-TLX Performance (TLX-P)

Condition	Mean (n = 7)	Range
Cane	2.31 (±1.37)	[0.67, 4.20]
DSS	1.00 (±0.60)	[0.40, 2.00]
Cane&DSS	1.68 (±0.75)	[0.53, 2.67]

7.6.3.5 Perceived Effort

As shown in Table 7-11, TLX-E was lowest under the DSS condition at 2.56 (±1.99). TLX-E had a mean of 2.71 (±1.97) under the Cane&DSS condition and a mean of 2.99 (±2.15) under the Cane condition. Effort was normally distributed under the Cane and the DSS conditions (Cane: p=0.474; DSS: p=0.070) but was not normally distributed under the Cane&DSS condition (Cane&DSS: p=0.001). There was not a statistically significant difference between conditions ($\chi^2(2, N = 7) = 0.286$, p=0.867).

Table 7-11: NASA-TLX Effort (TLX-E)

Condition	Mean (n = 7)	Range
Cane	2.99 (±2.15)	[0.40, 6.00]
DSS	2.56 (±1.99)	[0.67, 6.67]
Cane&DSS	2.71 (±1.97)	[1.60, 7.00]

7.6.3.6 Frustration

As shown in Table 7-12, TLX-F was lowest under the DSS condition at 0.96 (±1.65). TLX-F had a mean of 1.50 (±1.98) under the Cane&DSS condition and a mean of 2.22 (±2.34) under the Cane condition. TLX-F was normally distributed under the Cane and the Cane&DSS conditions (Cane: p=0.085; Cane&DSS: p=0.053) but was not normally distributed under the DSS condition (DSS: p=0.0001). There was not a significant difference between conditions ($\chi^2(2, N = 7) = 3.714$, p=0.156).

Table 7-12: NASA-TLX Frustration (TLX-F)

Condition	Mean (n = 7)	Range
Cane	2.22 (±2.34)	[0, 7.00]
DSS	0.96 (±1.65)	[0, 4.67]
Cane&DSS	1.50 (±1.98)	[0, 5.00]

7.6.3.7 Total Workload

As shown in Table 7-13, Total Workload (TLX-TWL) was lowest under the DSS condition at 9.30 (±3.59). TLX-TWL had a mean of 10.72 (±5.00) under the Cane&DSS condition and a mean of 12.82 (±4.45) under the Cane condition. TLX-TWL was normally distributed under all three experimental conditions (Cane: p=0.262, DSS: p=0.197, Cane&DSS: p=0.273). There was not a significant difference in TLX-TWL between conditions (F[2, 12]=2.160, p=0.158).

Table 7-13: NASA-TLX Total Workload (TLX-TWL)

Condition	Mean (n = 7)	Range
Cane	12.82 (±4.45)	[7.73, 18.40]
DSS	9.30 (±3.59)	[5.67, 14.47]
Cane&DSS	10.72 (±5.00)	[5.33, 17.27]

7.7 DISCUSSION

7.7.1 Collisions

As we hypothesized, results from this study indicated that the DSS will promote safe navigation by reducing the number and severity of collisions. Participants had significantly more Type I, Type II, Type III and total collisions when using just the cane than when using the cane in combination with the DSS or when using the DSS alone. Most of the collisions that occurred when using the DSS were of very low severity (mainly Type I).

Unlike the participants in Studies 1-3, the participants in this study had significant expertise with using a cane and were skilled in navigating without visual cues. However, participants had very little experience using a powered wheelchair, which explains the large number of severe (Type II and Type III) collisions that occurred when participants were using the cane alone.

7.7.2 Task Completion Time

TCT was lower when using the cane in comparison to the DSS alone but this difference was not significant so the hypothesis Q2 was not supported. Lower task completion time with the cane was achieved at the expense of hitting significantly more obstacles as shown in Figure 7-3. Subjects in this study had significant expertise with using a cane. This expertise was primarily responsible for the lower task completion time with the cane alone.

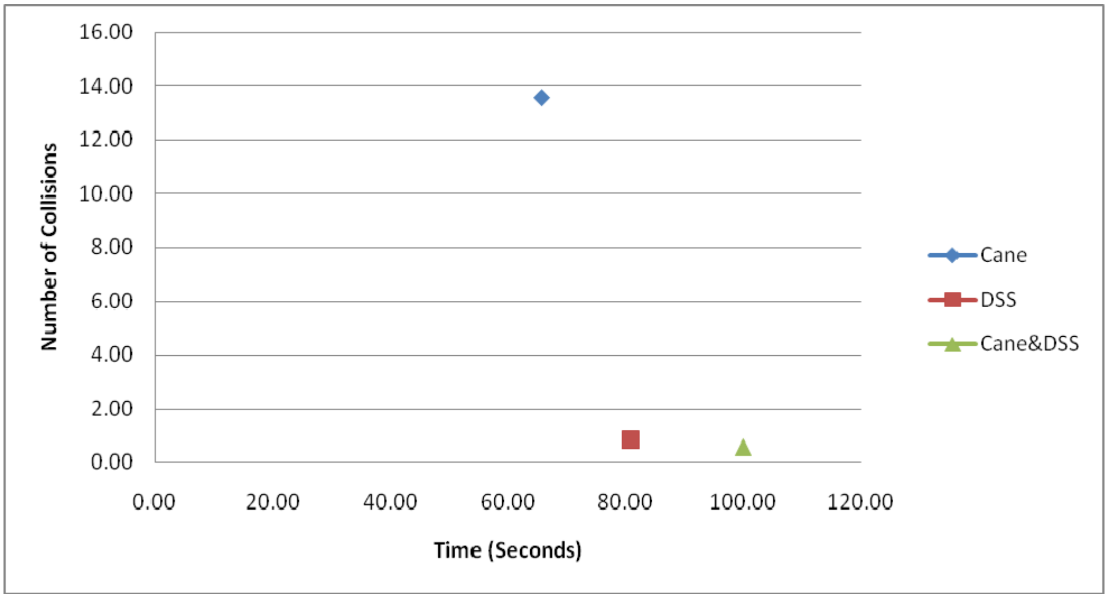


Figure 7-3: Collisions Vs Task Completion Time

7.7.3 Physical Demand

As hypothesized, physical demand was significantly higher when using the cane. It should be noted; however, that physical demand was still low (1.56 on a scale of 0 to 7) under the cane condition so it is unclear whether physical demand was actually problematic.

7.7.4 Mental Demand

The hypothesis that mental demand would be greater when using the cane alone was not supported. There was not a significant difference between conditions. Mental demand was high under all three conditions, however, indicating that subjects experienced significant mental demand.

7.7.5 Frustration

The hypothesis that frustration would be significantly higher when using the cane alone was not supported. There was not a significant difference in frustration between conditions. In addition, frustration was not particularly high under any condition.

7.7.6 Perceived Effort

The hypothesis that perceived effort would be greater when using the cane alone was not supported. There was not a significant difference between conditions. Perceived effort was high under all three conditions, however, indicating that subjects felt they exerted noticeable effort under all three conditions.

7.7.7 Total Workload

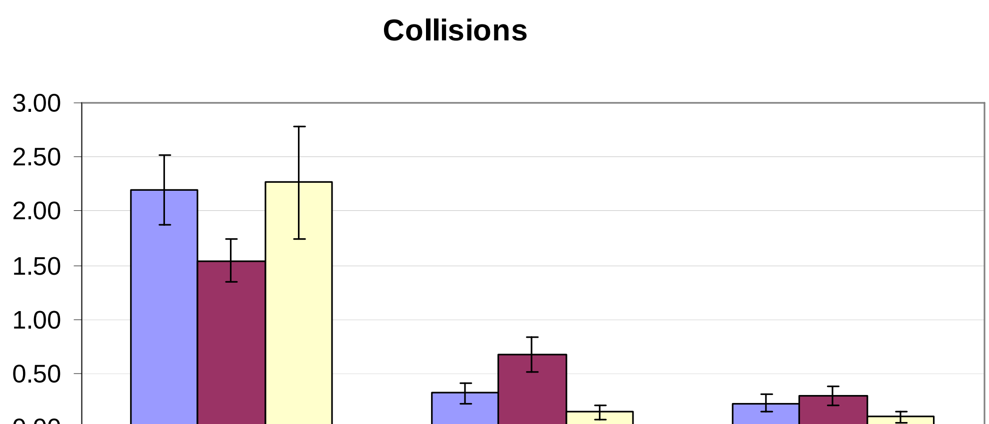
The hypothesis that total workload would be greater when using the cane alone was not supported. There was not a significant difference between conditions.

7.8 COMPARING STUDIES 1, 3 AND 4

Like the participants in Studies 1 and 3 the participants with visual impairments who participated in Study 4 were not experienced wheelchair users but were experienced at navigating without sight using a white cane. Unlike the able-bodied participants from Studies 1 and 2, however, these participants were skilled cane users and were familiar with the navigation strategies used by people with visual impairments.

7.8.1 Collisions

Collisions per navigation trial for participants with visual impairment was significantly lower than O&M Specialists (*p*=0.047) when using the DSS alone but there was no difference when using the cane alone or cane along with the DSS (Cane: p=0.830; Cane&DSS: p=0.693).

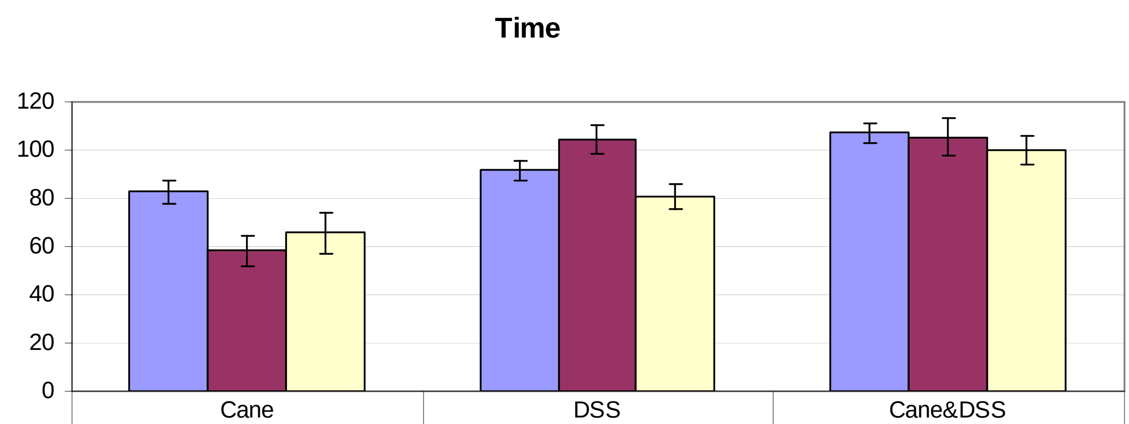


	Cane	DSS	Cane&DSS
Able body	2.19	0.32	0.23
O&M	1.54	0.67	0.29
Blind	2.26	0.14	0.10

Figure 7-4: Total Number of Collisions per Trial from Study 1, Study 3, and Study 4

7.8.2 TCT

There was no difference in the task completion time (TCT) between participants in Study 4 and in Study 1 (Cane: p=0.223 ; DSS: p=0.54) .TCT for participants with visual impairments was significantly lower than O&M Specialists (*p*=0.045) when using the DSS alone but there was no difference when using the cane alone or cane along with the DSS.



	Cane	DSS	Cane&DSS
Able body	82.68	91.52	107.24
O&M	58.19	104.29	105.52
Blind	65.71	80.88	100.02

Figure 7-5: Task Completion Time from Study 1, Study 3, and Study 4

7.8.3 Mental Demand

There was no difference in the mental demand between participants with visual impairments and participants in Study 1 (Cane: p=0.998 ; DSS: p=0.189 ; Cane&DSS: p=0.998), and between participants with visual impairments and O&M Specialists (Cane: p=0.796 ; DSS: p=0.998 ; Cane&DSS: p=0.458) .

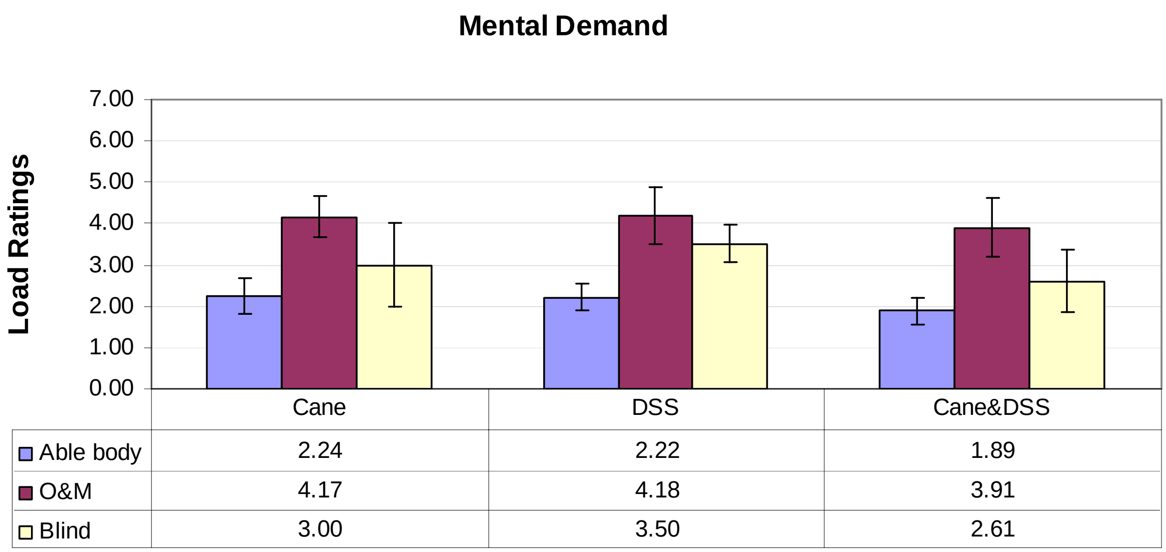
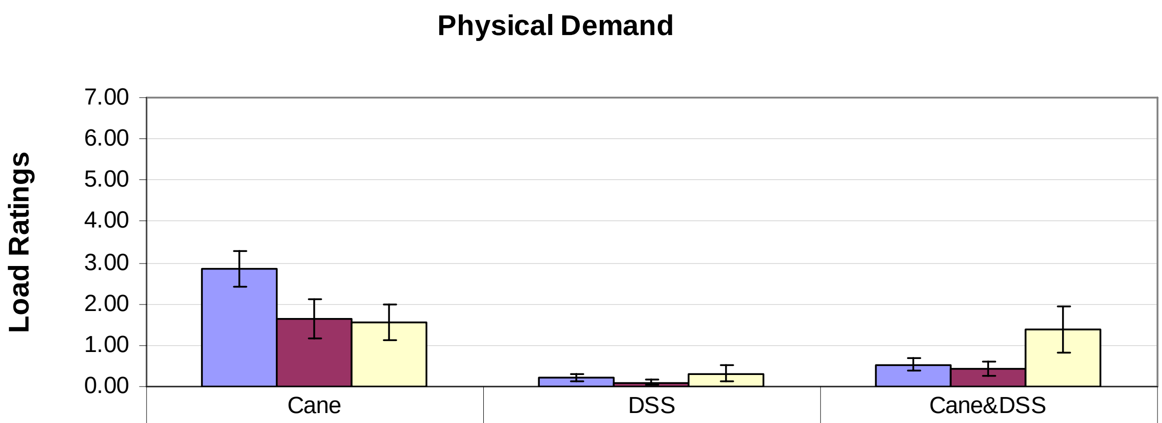


Figure 7-6: Mental Demand from Study 1, Study 3, and Study 4

7.8.4 Physical Demand

There was no difference in the physical demand between Study 1 and Study 4 (Cane: p=0.252 ; DSS: p=0.998 ; Cane&DSS: p=0.109), and between Study 3 and Study 4 (Cane: p=0.998 ; DSS: p=0.712 ; Cane&DSS: p=0.130) .

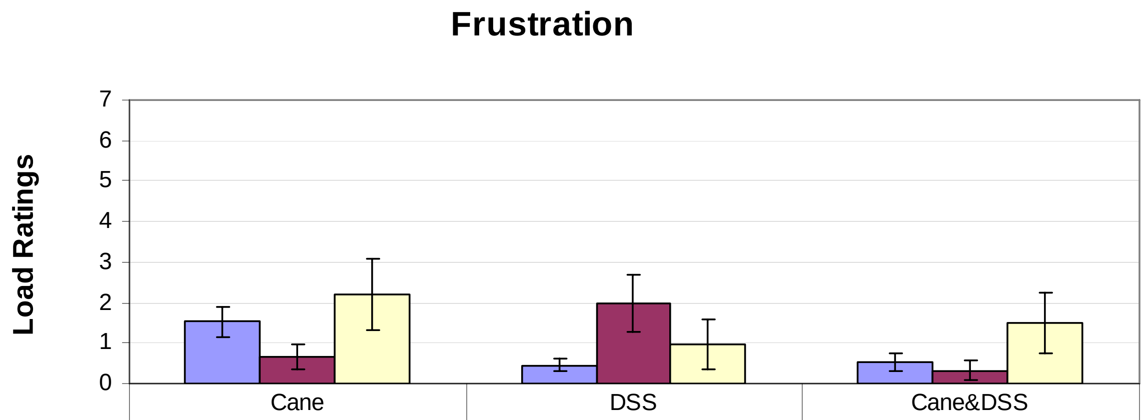


	Cane	DSS	Cane&DSS
Able body	2.84	0.22	0.53
O&M	1.64	0.10	0.43
Blind	1.56	0.31	1.38

Figure 7-7: Physical Demand from Study 1, Study 3, and Study 4

7.8.5 Frustration

There was no difference in the frustration experienced by participants with visual impairments and participants in Study 1 (Cane: p=0.998 ; DSS: p=0.998 ; Cane&DSS: p=0.235), and between participants with visual impairments and O&M Specialists (Cane: p=0.227 ; DSS: p=0.423 ; Cane&DSS: p=0.211) .



	Cane	DSS	Cane&DSS
Able body	1.53	0.45	0.53
O&M	0.65	1.98	0.33
Blind	2.22	0.96	1.50

Figure 7-8: Frustration from Study 1, Study 3, and Study 4

7.8.6 Perceived Effort

There was no difference in the perceived effort between participants with visual impairments and O&M Specialists (Cane: p=0.998 ; DSS: p=0.998 ; Cane&DSS: p=0.691). Perceived effort for participants with visual impairment was significantly higher than participants in Study 1 (*p*=0.038) when using the DSS alone but there was no difference when using the cane alone or cane along with the DSS (Cane: p=0.998 ; Cane&DSS: p=0.209).

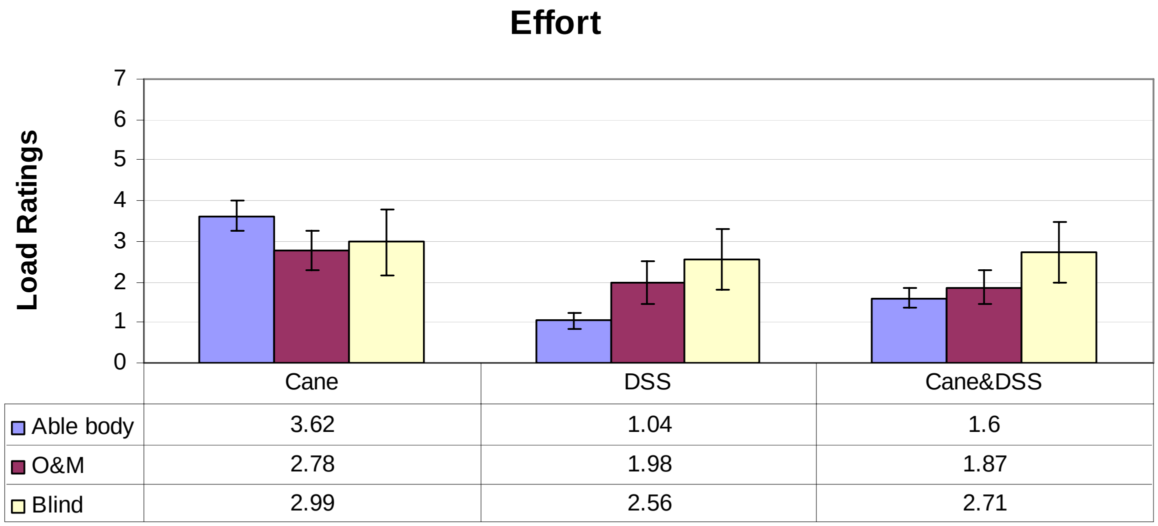
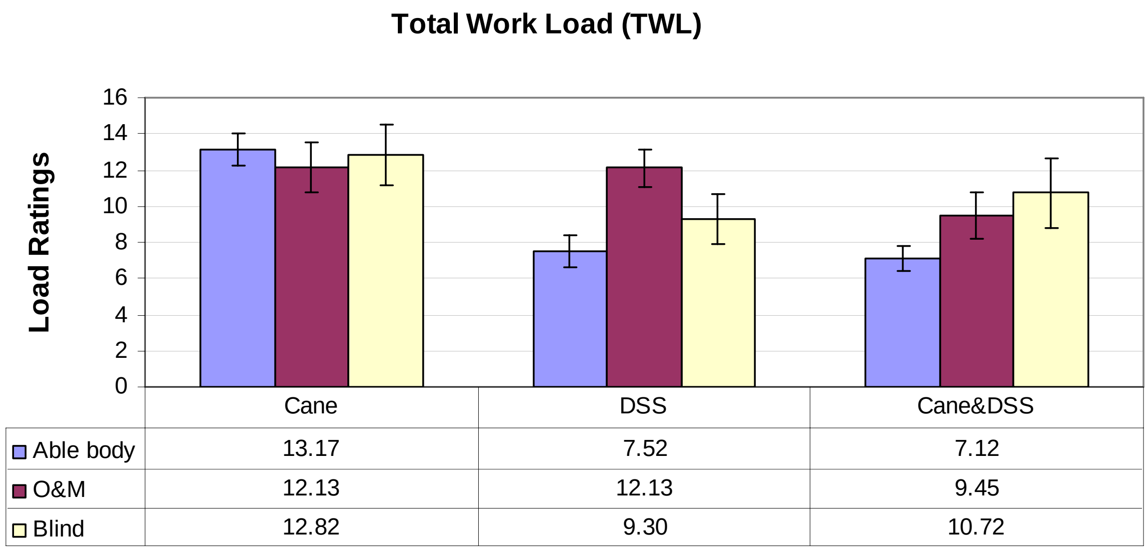


Figure 7-9: Perceived Effort from Study 1, Study 3, and Study 4

7.8.7 TLX-TWL

There was no difference in the Total Work Load (TWL) scores between participants with visual impairments and participants in Study 1 (Cane: p=0.998 ; DSS: p=0.331 ; Cane&DSS: p=0.246), and between participants with visual impairments and O&M Specialists (Cane: p=0.998 ; DSS: p=0.238 ; Cane&DSS: p=0.998) .



	Cane	DSS	Cane&DSS
Able body	13.17	7.52	7.12
O&M	12.13	12.13	9.45
Blind	12.82	9.30	10.72

Figure 7-10: TWL from Study 1, Study 3, and Study 4

7.9 CONCLUSIONS

Several of the hypotheses were not supported. Participants with visual impairments did not experience any significant difference in mental demand, perceived effort, frustration or total workload. Participants felt less physical demand when driving the wheelchair while receiving navigation assistance from the DSS. The results from this study were consistent with Study 1 in that use of the DSS reduced collisions of medium and high severity, but this increased safety is achieved at the expense of increased task completion time. Many results from this study showed the difference in dependent variables in experimental conditions but this difference could not reach on significance because of the small sample size.

8.0 STUDY 5: PARTICIPANTS WITH VISUAL AND MOBILITY IMPAIRMENTS

8.1 INTRODUCTION

Study 5 employed two subjects who had both visual impairments and mobility impairments. Study with there participants were designed as per Single subject designs (SSD). Single subject designs (SSD) are typically used to study the behavioral change an individual exhibits as a result of some intervention. In single-subject designs, each participant serves as her or his own control, the participant is exposed to a baseline (non-treatment) and a intervention (treatment) phase and performance is measured during each phase. SSD is an appropriate way to analyze the effect of the DSS on the navigation performance on the intended population as:

- People with multiple disabilities have so much variability that it is difficult to get enough subjects with similar medical conditions that can provide statistically significant information about the DSS navigation performance as a group.
- Diverse groups of people with disabilities can benefit from the navigation assistance provided by the DSS and it is difficult to get enough participants from all these groups who can participate.

8.2 SPECIFIC AIMS AND HYPOTHESES

The purpose of this study was to determine if the DSS provides effective independent mobility to participants with visual and mobility impairments.

Specific Aim 1. To evaluate the effectiveness of the DSS versus cane on a forward moving navigation task based on quantitative measures such as number of collisions and task completion time. Following hypotheses were associated with the specific aim 1:

Hypothesis Q1. Participants will have fewer collisions when using the DSS than when using a cane.

Hypothesis Q2. The average time of completion for a task will be greater when using the DSS in comparison to a cane.

Specific Aim 2. To evaluate the subjective workload associated with the use of the DSS on a navigation task and compare it with the subjective workload associated with the use of a cane on the similar navigation task. Following hypotheses were associated with the specific aim 2:

Hypothesis S1. Perceived physical demand in a given navigation task will be lower when using the DSS than when using a cane.

Hypothesis S2. Perceived mental demand will be higher when using the DSS than when using a cane.

Hypothesis S3. Frustration when using the DSS will be lower than when using a cane.

Hypothesis S4. Perceived effort when using the DSS will be lower than when using a cane.

Hypothesis S5. TWL when using the DSS will be lower than when using a cane.

Specific Aim 3. To evaluate the performance and robustness of the DSS based on the objective measures (e.g. number of collisions, task completion time, number of system resets required during the trials, errors in the architecture) and subjective measures (e.g. workload, users' recommendation, investigators observation of users' performance) and, based on the results, determine the changes required in the hardware (e.g., electronics and sensor housings, mountings), software (e.g., slow threshold, stop threshold) and user interface (e.g., auditory feedback, visual feedback).

8.3 SUBJECTS

8.3.1 Recruitment

The study protocol was approved by the Institutional Review Board (IRB) of the University of Pittsburgh on March 10, 2008. A further modification in the study protocol was accepted by the IRB on September 3, 2008, after which the recruitment process was begun. Two Subjects with mobility and visual impairments were recruited from the Center for Assistive Technology (CAT) patient database on the recommendations of their clinicians.

8.3.2 Inclusion / exclusion

Inclusion criteria for the participants were:

- Be older than 21 years of age
- Have both a mobility impairment and a visual impairment

- Have experience using a powered wheelchair
- Have normal hearing ability
- Be available to finish the trials in one or two sessions within a week

Exclusion criteria for participants were as follows:

- Do not have any medical condition that would interfere with driving a wheelchair, such as nausea or dizziness.
- Do not have complex seating and positioning needs.

8.3.3 Demographics

Two participants, both females, were recruited for this study.

8.3.3.1 Subject A

Subject A is a 55-year-old Caucasian single female with a primary diagnosis of Cerebral Palsy and secondary diagnosis of visual impairment. She has arthritis in both of her shoulders and elbows. She has used a powered wheelchair (Permobil C-300) regularly for the past seven years. Prior to that, she used a one arm manual wheelchair for 16 years. She switched from a one arm manual wheelchair to a powered wheelchair because the arthritis in her shoulders and elbows made it difficult for her to push a wheelchair manually.

Subject A uses a four feet long telescopic white cane for navigation assistance on her powered wheelchair. She lives in a one bedroom apartment and most of her wheelchair usage is indoors. She reported regular collisions at her home when driving her powered wheelchair because of her inability to use the cane effectively due to her arthritis. Fear of collisions always prevents her from driving the wheelchair independently on many occasions.

8.3.3.2 Subject B

Subject B is 62-year-old Caucasian married female with a primary diagnosis of Multiple Sclerosis (MS) and secondary diagnosis of visual impairment. She has used a powered wheelchair since 2005 and used a manual wheelchair for ten years prior. She switched to a powered wheelchair because she did not have the stamina needed to propel a manual wheelchair. Using a powered wheelchair allowed her to conserve energy and participate in activities of daily living. It was difficult for her to use a cane with her powered wheelchair because the necessary physical effort caused fatigue. She drives her wheelchair with her right hand and uses her left hand to identify environmental cues and obstacles detection. Most of her wheelchair usage is indoors. She drives her chair at very low speed in her home and still reports regular collisions. She is not confident in using her powered wheelchair because she fears personal injury and property damage. Outside her home she is pushed by a caregiver in her manual wheelchair.

Table 8-1: Demographics

	Participant A	Participant B
Age	55	62
Gender	Female	Female
Primary Diagnosis	CP	MS
Secondary Diagnosis	Visual Impairment	Visual Impairment
Manual Wheelchair usage	16 years	10 Years
Powered Wheelchair usage	7 years	3 Years
Navigation Assistance	Cane	Hand

8.4 METHODS

8.4.1 Informed Consent

Prior to participating in the study, the investigator read and explained each section of the Informed Consent Form to each participant. Once each participant indicated that the form had been understood, and agreed to participate, the informed consent form was signed. A copy of the informed consent form was given to the participants upon completion of the experiment.

8.4.2 Seating and Positioning

Depending upon participants' requirements, the seating and positioning of the wheelchair was adjusted by the investigator. For example, the wheelchair joystick was mounted on the right or the left side of the wheelchair, depending upon whether the participant was left-handed or right-handed. Participant A required height adjustments of the footrests along with adjustments in the backrest angle. Participant B required adjustments in the footrests heights and additional support in the back.

8.4.3 Training

Participants completed the same training activities as participants in Study 1 (see Section 4.4.2.3) except that participant B used her hand rather than a cane.

8.4.4 Protocol

A single-subject, single-baseline, AB design was used to evaluate the performance of the DSS:

PHASE A: (Baseline Condition): Each participant drove the experimental wheelchair (Quantum-600) with his or her own method of navigation (i.e., subject A used a cane in baseline for navigation assistance while subject B used her hands for navigation assistance).

PHASE B: (Intervention Condition): Each participant drove the experimental wheelchair with navigation assistance from the DSS.

The same protocol for each trial used in Study 1 (see Section 4.4.2.4) was followed. Subject A completed nine baseline trials and 14 intervention trials. Subject B completed six baseline trials and nine intervention trials.

8.4.5 Data collection

Matching Person with Technology (MPT) questionnaire: After participants were done with all the trials they were asked to fill out the Matching Person with Technology (MPT) questionnaire (see Appendix D). MPT evaluates and compares the usefulness of various types of navigation assistance devices such as cane or DSS with a powered wheelchair in every day activities. Participants evaluated each question in the MPT questionnaire on the scale from 0 to 5. In addition, all of the measures used in Study 1 (see Section 4.4.2.5) were collected.

8.5 DATA ANALYSIS

Various approaches of single subject design (SSD) data analysis were used to analyze the effectiveness of the DSS in improving navigation performance. These data analysis approaches included traditional graphical visual analyses [63], specialized semi-statistical analyses (Celeration Line and the test of serial dependency using Bartlett's test of the lag-1 autocorrelation coefficients) [63, 64], and statistical procedures (Tryon's C-Statistics) [65]. Microsoft[6] Excel 2003 was used for all the analyses.

Prior to any analysis, serial dependence of the baseline phase was determined by computing the degree of autocorrelation within the baseline data. Bartlett's test was used to determine the statistical significance of the calculated autocorrelation coefficient. If the autocorrelation coefficient was greater than $2/\sqrt{n}$, (where n was the number of observations in the baseline phase) the baseline data was considered serially dependent and only the C Statistic method was used for the analysis of this serially dependent data. Data which was not serially dependent was analyzed using all three analysis techniques: graphical visual, semi-statistical, and statistical.

Analysis began with a basic visual inspection of the data. For visual analysis, data were plotted and phase transitions were marked with a vertical line dividing each phase. Mean lines were then added as horizontal lines passing through the mean for each phase data set. In addition, trend lines for each data set were added to the graphed data for comparison purposes. Finally, these data were inspected and a judgment was made as to whether the mean or trend of the data differed across phases.

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[6] Microsoft Corp. Seattle, WA

The Celeration line, or split middle, procedure was used to determine the presence of a significant trend in the data across baseline and intervention phases. The baseline data was divided in half and the median of each half was calculated. The trend line was plotted in the graphed data by using these two medians as the reference points. This trend line was extended into the intervention phase as the Celeration line (represented as a dashed line), which represents the expected trend if there was no intervention. Bloom's probability table [63] was used to determine whether the change in the proportion of data points above or below the Celeration line was statistically significant across baseline phase and intervention phase at the $p < 0.05$ level (one tailed).

The final statistical analysis method used, was the Tryon's C Statistic method. The C Statistic method is designed to evaluate treatment interventions with small data sets (Tryon, 1982). The C Statistic method was applied to the data in the baseline phase. If the Z-score indicated there was not a significant trend in the baseline data ($Z<1.64$), then the baseline and intervention phase data were combined and the C Statistic method was applied to this combined data set. If the z-score indicated there was a significant trend in the combined data set ($Z>1.64$) then effect of the intervention was considered significant.

If, however, the Z-score for the baseline data was found to be significant ($Z >1.64$), analysis of the baseline and intervention data was performed using the comparison series approach. A comparison series was created by subtracting the baseline phase data from the intervention phase data. The maximum number of data values possible in the comparison is always equal to the number of data points in the baseline. This comparison series was then tested for significance using the same C Statistic analysis.

8.6 RESULTS

8.6.1 Subject A

Baseline data for all the dependent variables (Type I Collision, Type II Collisions, Type III Collision, Total Collisions, and Trial Completion Time) were not considered serially dependent because Bartlett test on the baseline of all the DV's revealed no statistically significant degree of autocorrelation (see Table 8-2). All the visual graphical analysis, Celeration line, and Tryon's C Statistics tests were performed on all the DV's.

Table 8-2: SSD Analysis Results Summary for Subject A

Test / Variable	Serial Dependence	Celeration Line Significance	Tryon's C-Statistics		
			Z_A	Z_{AB}	Significance
Type I Collision	No	**Yes**	-0.08	0.64	No
Type II Collision	No	No	-0.57	0.99	No
Type III Collision	No	**Yes**	1.59	3.58**	**Yes**
Total Collisions	No	No	-0.92	3.02**	**Yes**
Trial Completion Time	No	No	-2.57*	-1.05[a]	No

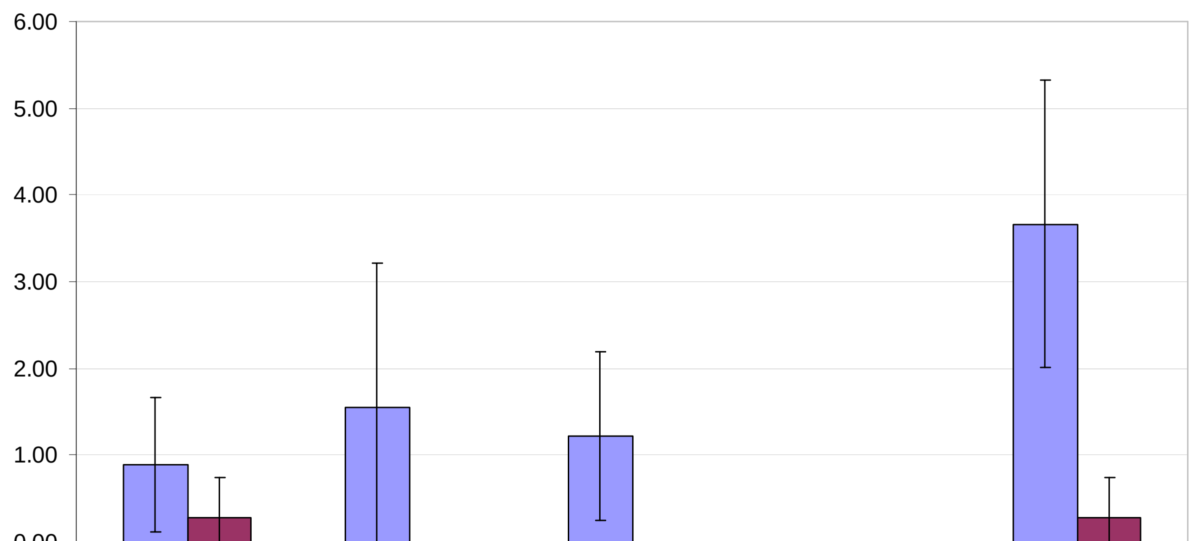
a Comparison series results

* $p<0.05$

** $p<0.001$

Table 8-3: Descriptive Statistics (Subject A)

	Baseline (Cane)				Intervention (DSS)			
Variable	Mean	SD	Min	Max	Mean	SD	Min	Max
Type I Collision	0.89	0.78	0.00	2.00	0.29	0.47	0.00	1.00
Type II Collision	1.56	1.67	0.00	5.00	0.00	0.00	0.00	0.00
Type III Collision	1.22	0.97	0.00	3.00	0.00	0.00	0.00	0.00
Total Collisions	3.67	1.66	1.00	6.00	0.29	0.47	0.00	1.00
Trial Completion Time	73.11	14.88	48.00	94.00	101.50	34.84	52.00	160.00



	Type I	Type II	Type III		Total
Cane	0.89	1.56	1.22		3.67
DSS	0.29	0.00	0.00		0.29

Figure 8-1: Collisions for Subject A

8.6.1.1 Type I Collisions

The mean of NCT-I in the intervention phase (M = 0.29, SD = 0.47) was lower than the mean of NCT-I in the baseline phase (M= 0.89, SD = 0.78).

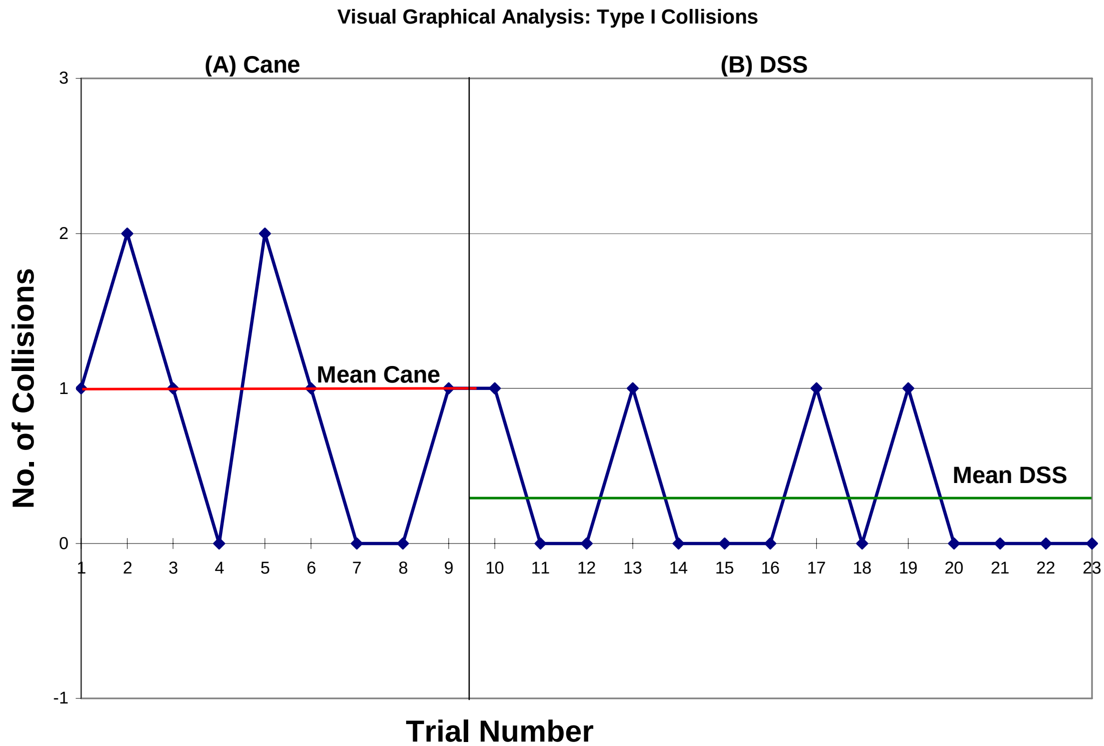


Figure 8-2: Number of Type I Collisions per Trial (Subject A)

During baseline 3 of 9 points were below the Celeration line, while during the intervention phase 10 of 14 points were below the Celeration line (see Figure 8-3). According to the Bloom probability table, this difference in proportions indicated that there was significant effect of intervention in reducing the number of Type I collisions ($p<0.05$).

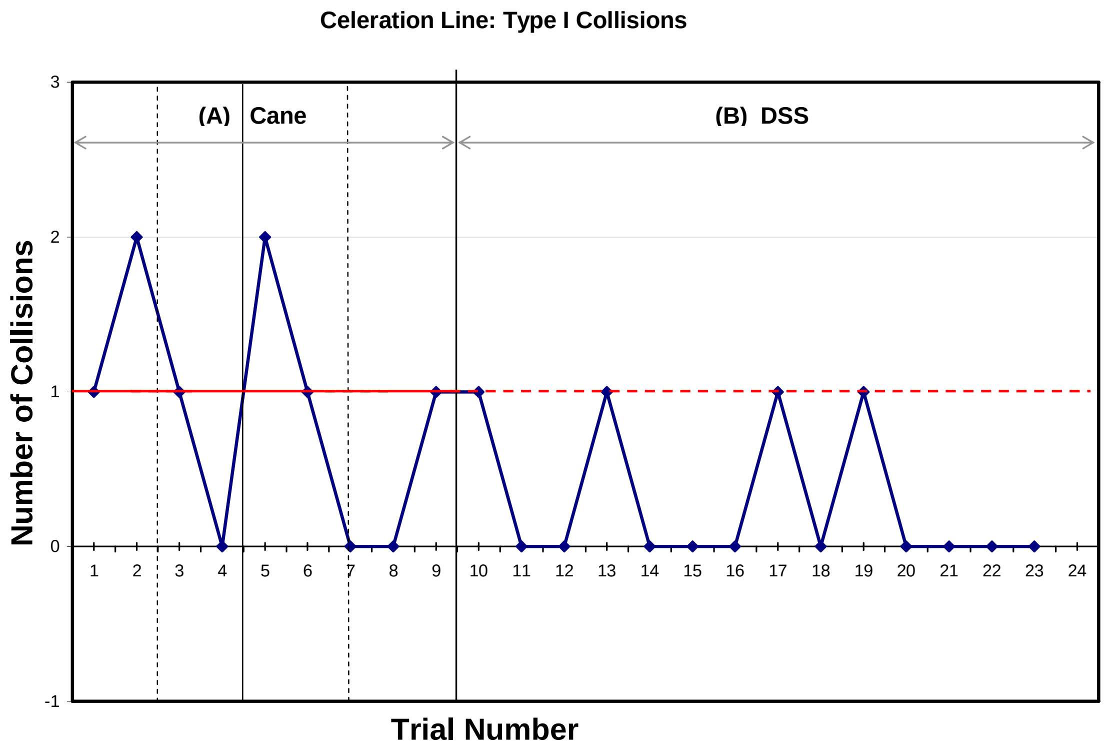


Figure 8-3 : Celeration Line for Type I Collisions (Subject A)

The C Statistic method indicated no significant trend in the Type I collisions baseline data. The C Statistic method on the combined baseline and intervention data indicated that effect of the DSS on reducing the Type I collisions was not significant ($z=0.64$, $p= 0.26$).

8.6.1.2 Type II Collisions

The mean NCT-II in the intervention phase (M = 0, SD = 0) was lower than the mean NCT-II in the baseline phase (M = 1.56, SD = 1.67).

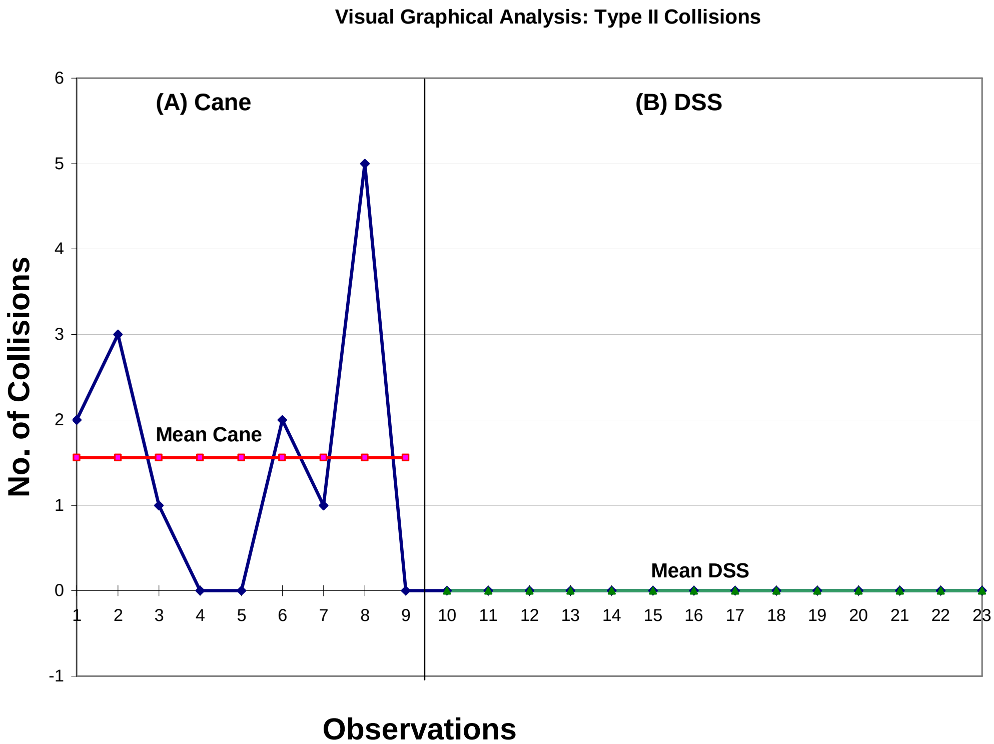


Figure 8-4: Number of Type II Collisions per Trial (Subject A)

During the baseline phase, 5 of 9 points were below the Celeration line, while during the intervention phase 6 of 14 points were below the Celeration line (see Figure 8-5). According to the Bloom probability table, this difference in proportions indicated that there was no significant effect of intervention in reducing the number of Type II collisions ($p>0.05$).

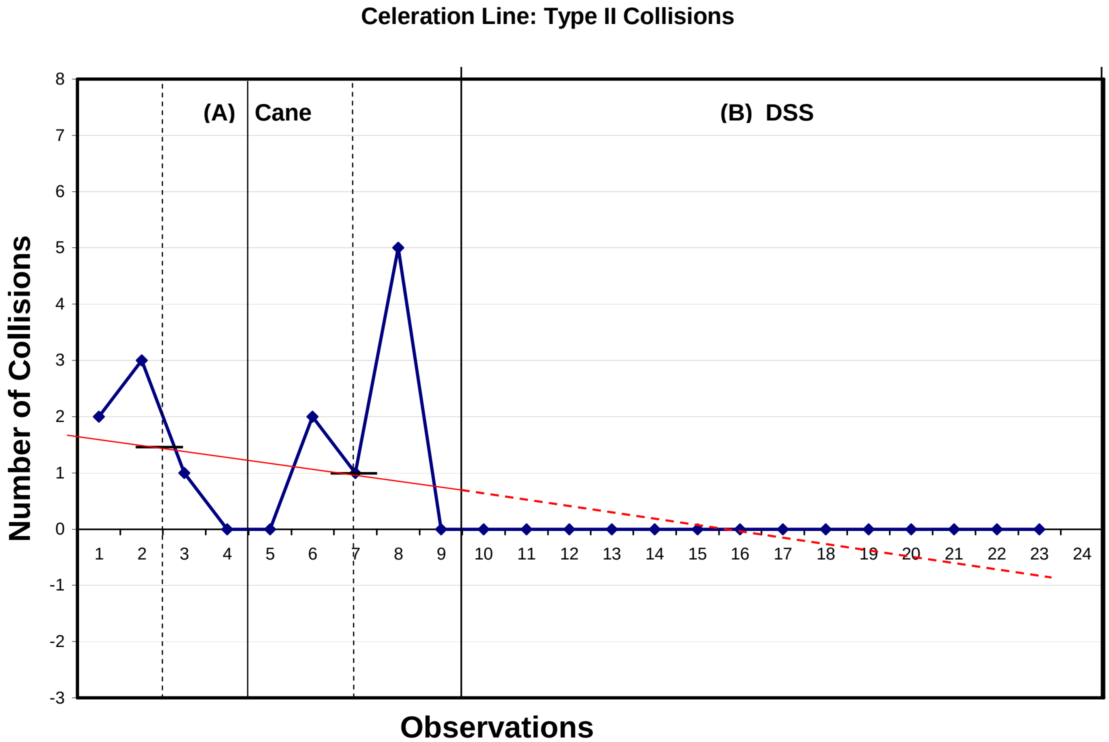


Figure 8-5: Celeration Line for Type II Collisions (Subject A)

The C Statistic method indicated no significant trend in the number of Type II collisions during baseline. The C Statistic method on the combined baseline and intervention data indicated that effect of the DSS on reducing the Type II collisions was not significant ($z = 0.99$, $p = 0.16$).

8.6.1.3 Type III Collisions

The mean NCT-III in the intervention ($M = 0$, $SD = 0$) phase was lower than the mean NCT-III in the baseline phase ($M = 1.22$, $SD = 0.97$).

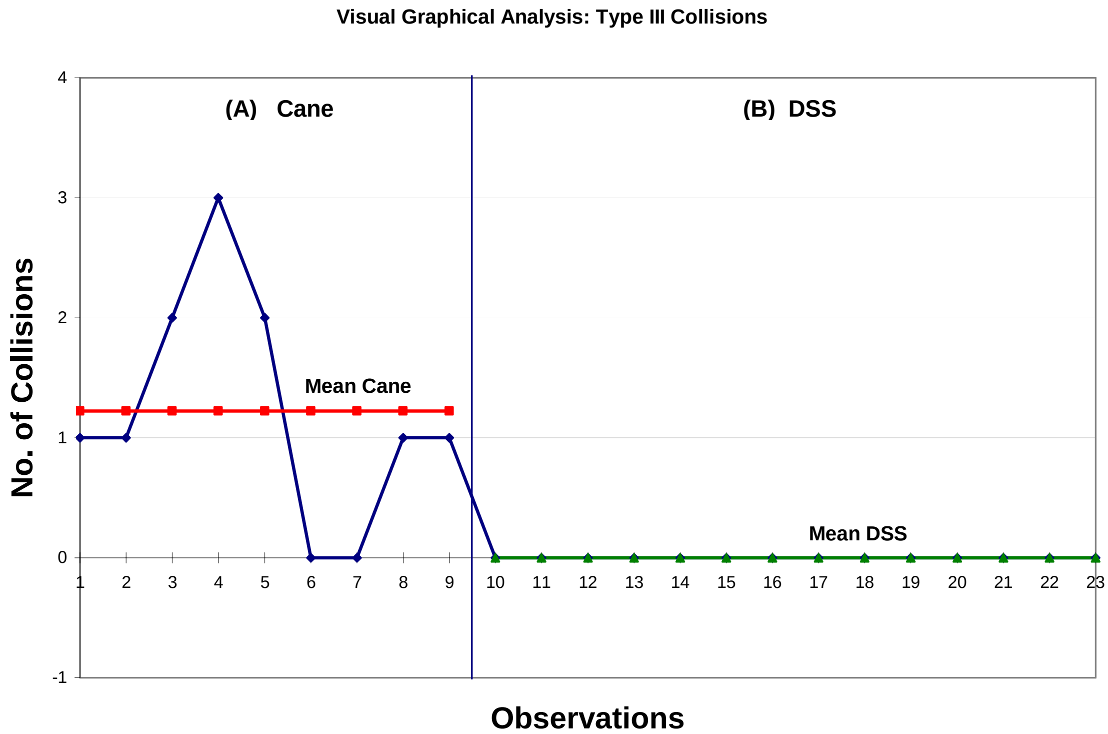


Figure 8-6: Number of Type III Collisions per Trial (Subject A)

During the baseline phase 4 of 9 points were below the Celeration line, while during intervention phase 10 of 14 points were below the Celeration line (see Figure 8-7). According to the Bloom probability table, this difference in proportions indicated that there was a significant effect of intervention in reducing the number of Type III collisions (p>0.05).

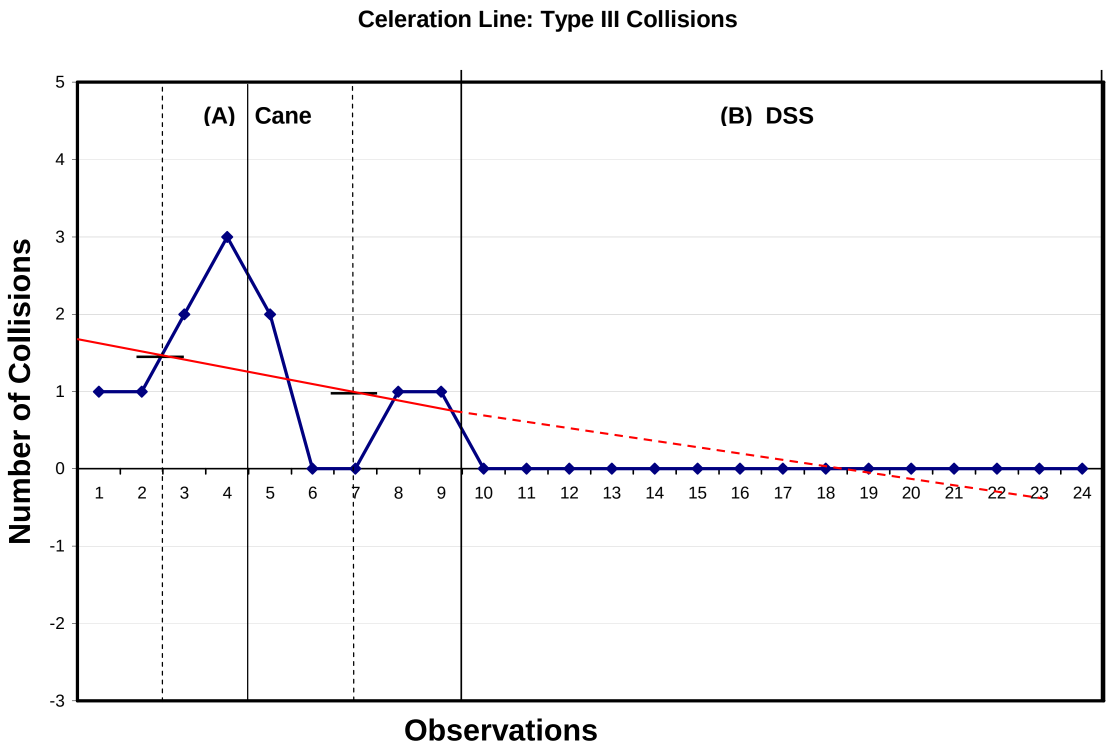


Figure 8-7: Celeration Line of Type III Collisions (Subject A)

The C Statistic method indicated no significant trend in the number of Type III collisions during baseline. The C Statistic method on the combined baseline and intervention data indicated that the effect of the DSS on reducing Type III collisions was statistically significant ($z = 3.58$, $p = 0.0001$).

8.6.1.4 Total Collisions:

The mean NCT-T in the intervention phase ($M = 0.29$, $SD = 0.47$) was lower than the mean NCT-T in the baseline phase ($M = 3.67$, $SD = 1.66$).

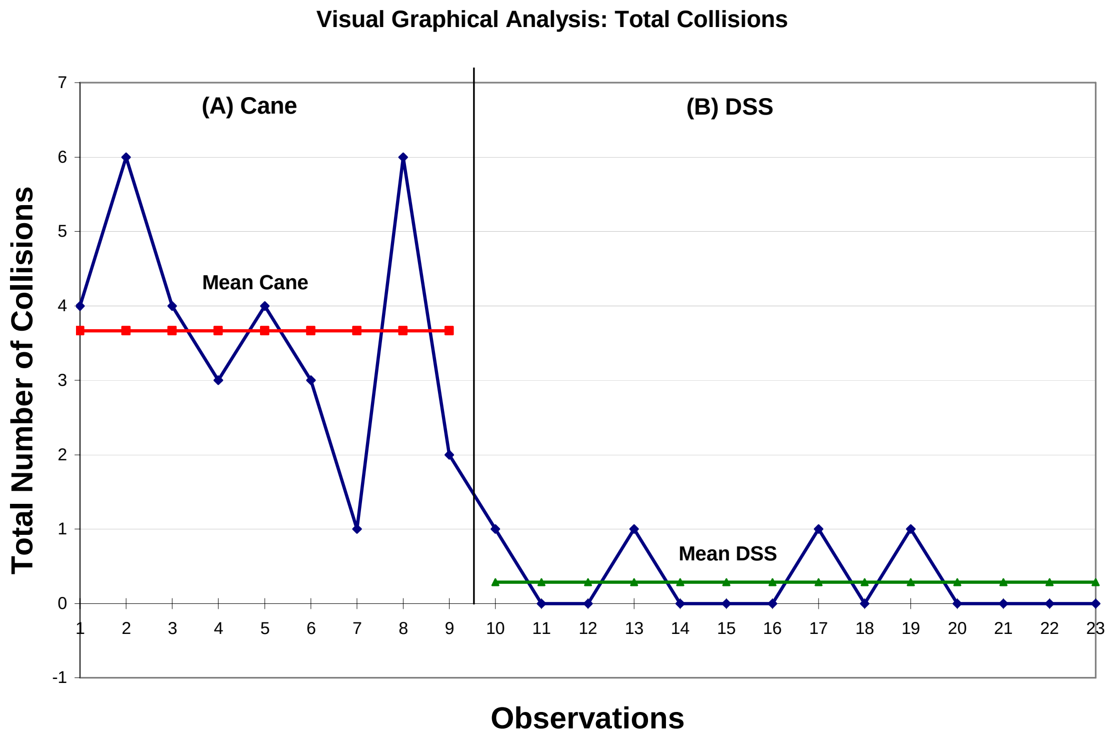


Figure 8-8: Total Number of Collisions per Trial(Subject A)

During the baseline phase 5 of 9 points were below the Celeration line, while during the intervention phase 9 of 14 points were below the Celeration line (see Figure 8-9). According to the Bloom probability table, this difference in proportions indicated that there was no significant effect of intervention in reducing the total number collisions ($p>0.05$).

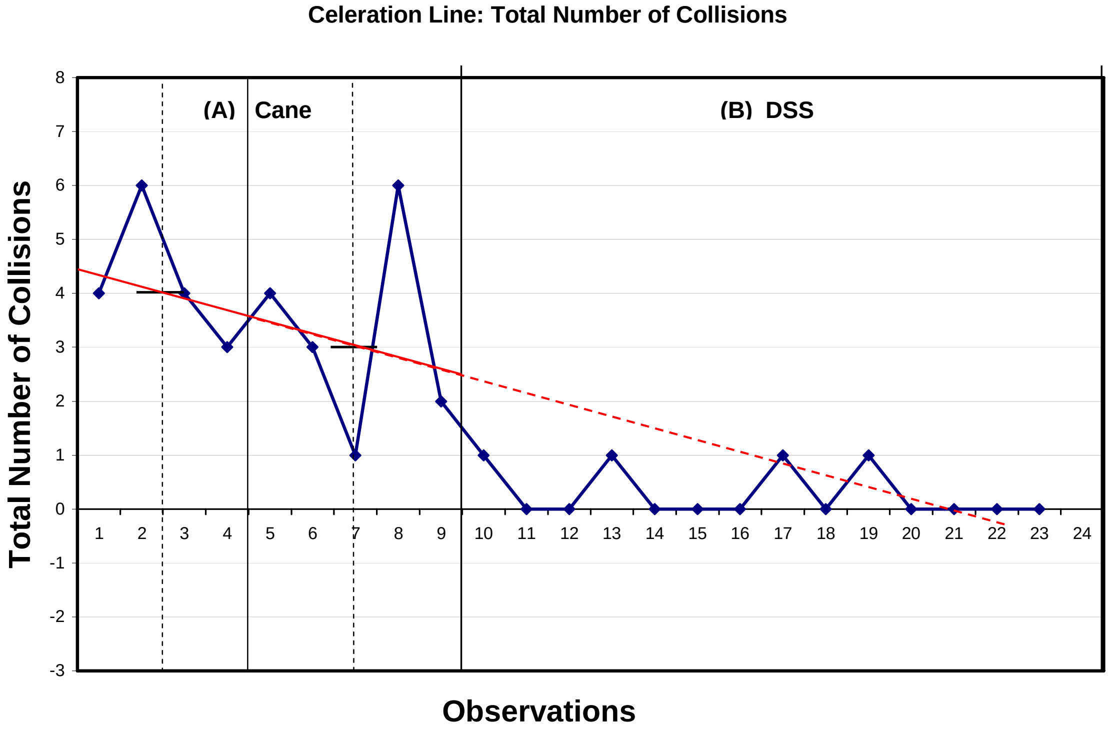


Figure 8-9: Celeration Line of Total Collisions (Subject A)

The C-statistics method indicated no significant trend in the total number of collisions during baseline. The C-statistics method on the combined baseline and intervention data indicated that the effect of the DSS on reducing the total number of collisions was significant ($z = 3.02$, $p = 0.001$).

8.6.1.5 Trial Completion Time

The average time to complete a trial in the intervention phase ($M = 101.50$, $SD = 34.84$) was higher than the average time to complete a trial in the baseline phase ($M = 73.11$, $SD = 14.88$).

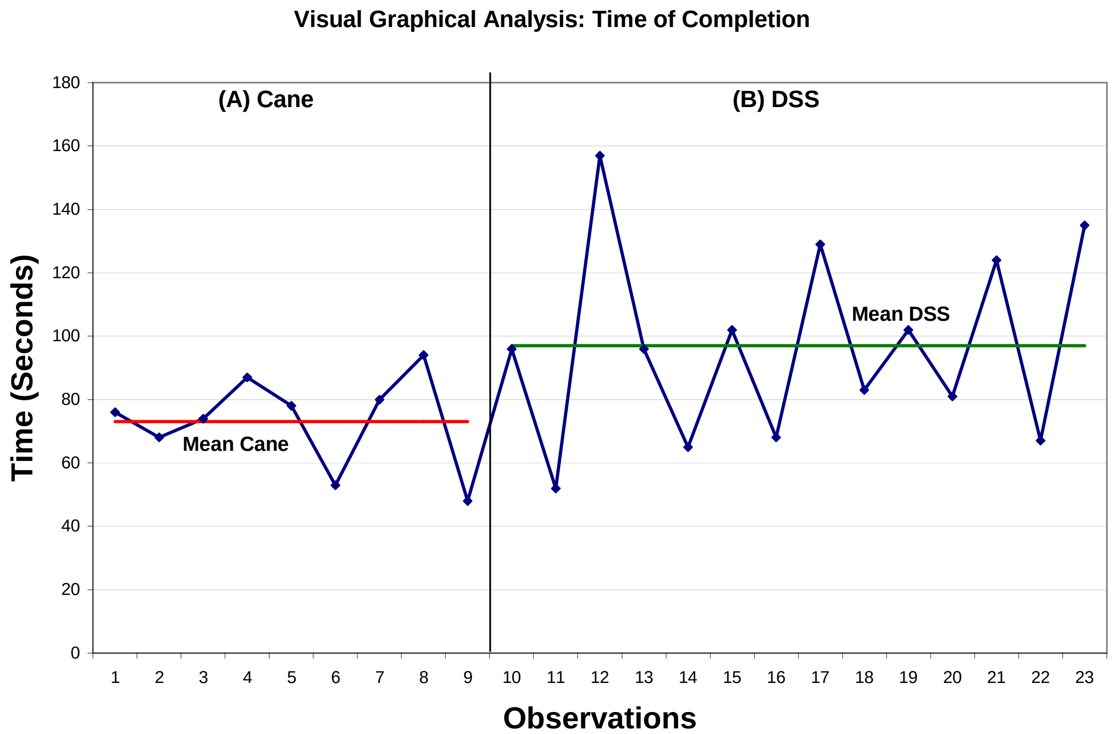


Figure 8-10: Trial Completion Time (Subject A)

During baseline phase 5 of 9 points were above the Celeration line while during the intervention phase 8 of 14 points were above the Celeration line (see Figure 8-11). According to the Bloom probability table, this difference in proportions indicated that there was no significant effect of intervention in reducing the time to finish a trial ($p>0.05$).

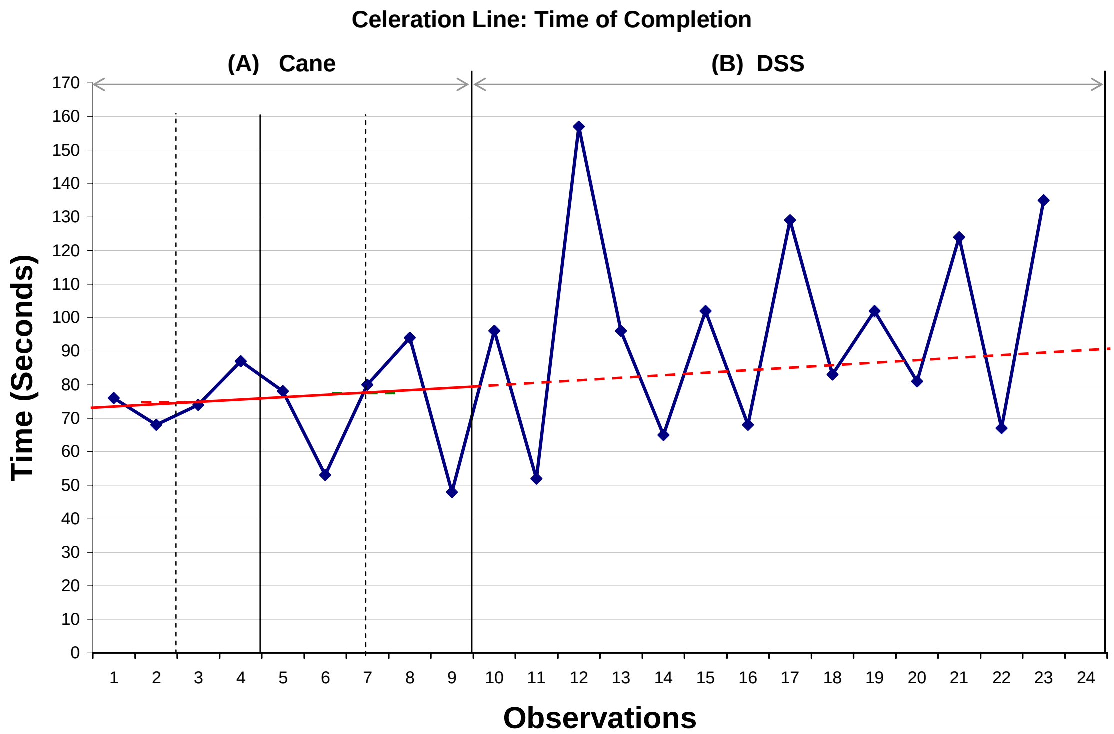
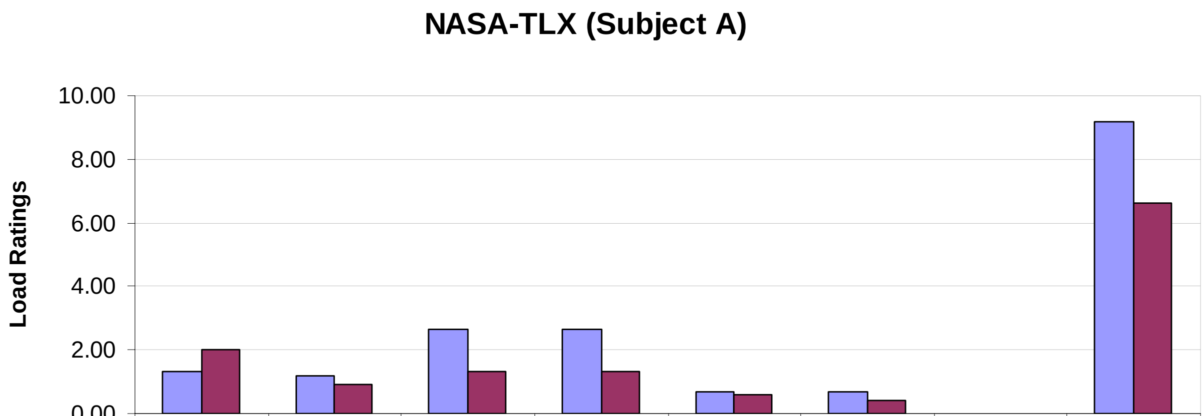


Figure 8-11: Celeration Line of Trial Completion Time

The C Statistic method indicated that there was a significant trend in Trial Completion Time ($Z = 2.57$, $p = 0.001$) during the baseline phase. A comparison series was developed by subtracting the baseline date from the corresponding intervention data and a C Statistic analysis was performed on the resulting series. Results indicated that use of the DSS increases the Trial Completion Time but this increase in time was not significant ($Z = 1.05$, $p = 0.15$).

8.6.1.6 NASA-TLX

The TLX-TWL when using the cane was higher in comparison to the DSS (see Figure 8-12). Physical demand, Temporal demand, Effort, and Frustration with the DSS was lower in comparison to cane. On the other hand, Mental demand with the DSS was higher in comparison to the cane.



	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration		Total Work Load
Cane	1.33	1.20	2.67	2.67	0.67	0.67		9.20
DSS	2.00	0.93	1.33	1.33	0.60	0.40		6.60

Figure 8-12: NASA-TLX Scores (Subject A)

8.6.1.7 Matching People with Technologies (MPT)

Subject A compared the DSS to her existing navigation assistance method on items that measured the compatibility of each method with various aspects of mobility (e.g. achieving goals, improving quality of life, feeling safe, fit in routine, fit in living space, comfortable in using home, work and community; see Figure 8-13). Each of these 12 items were scored on a scale from 0-5, where a lower number indicate low compatibility and a higher number indicated higher compatibility. The DSS scored 50 points while the cane scored 39 points (see Figure 8-13). Subject A did not rate the question related to the use of the device at work since she was not working.

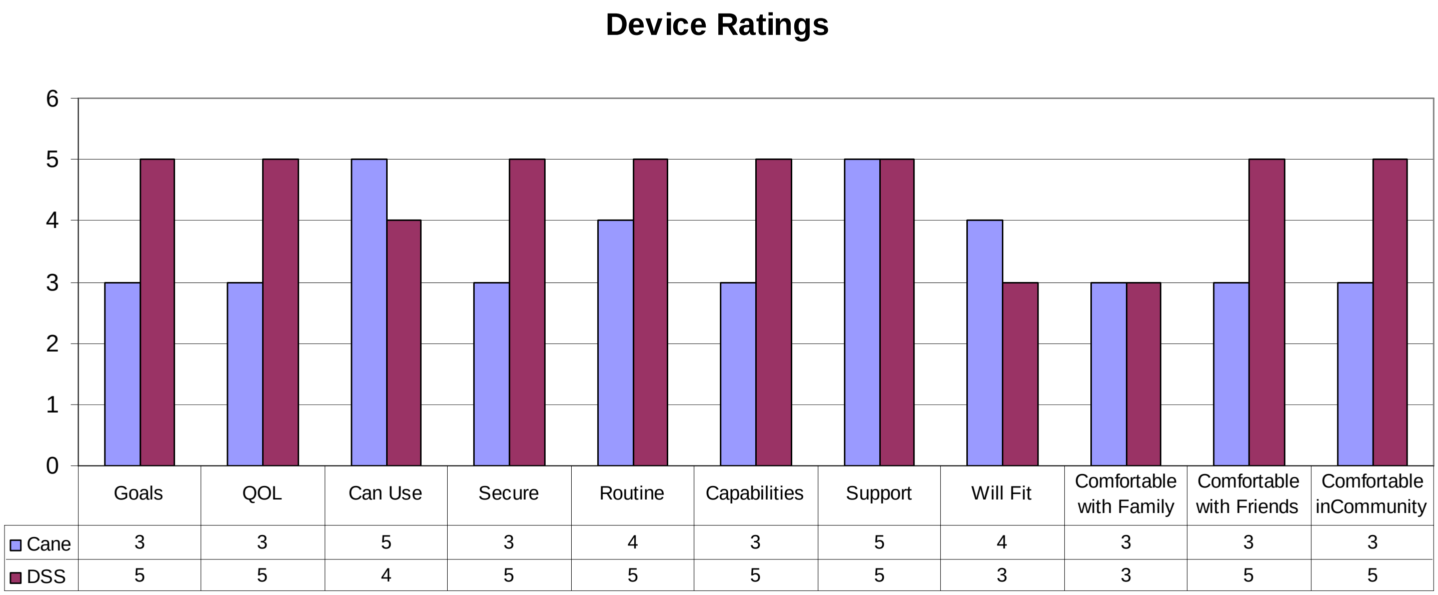


Figure 8-13: MPT Ratings

8.6.2 Subject B

Baseline data for all the dependent variables (Type I Collision, Type II Collisions, Type III Collision, Total Collisions, and Trial Completion Time) were not considered serially dependent because Bartlett test on the baseline of all the DV's revealed no statistically significant degree of autocorrelation (see Table 8-4). Visual graphical analysis, Celeration line method, and Tryon's C-Statistics tests were performed on all the DV's for Subject B.

Table 8-4: SSD Analysis Results Summary for Subject B

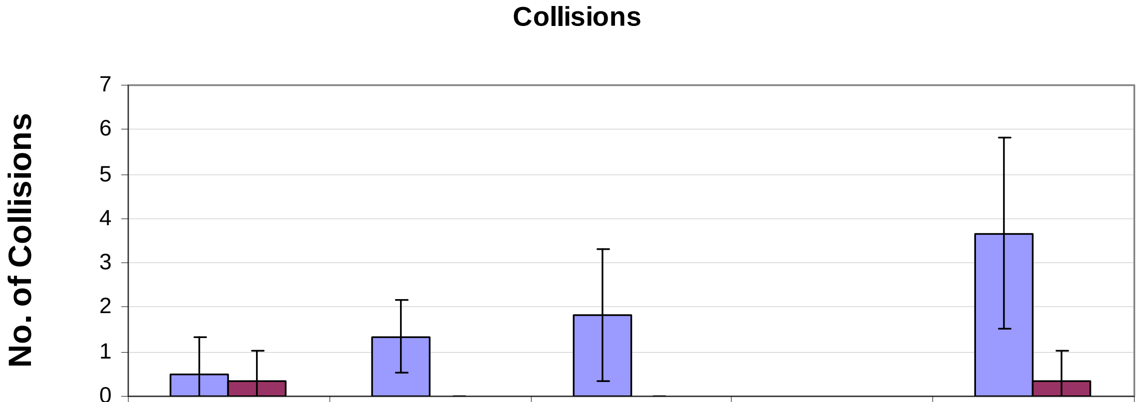
Test Variable	Serial Dependence	Celeration Line Significance	Tryon's C-Statistics Z_A	Z_{AB}	Significance
Type I Collision	No	**Yes**	0.85	1.97*	**Yes**
Type II Collision	No	**Yes**	-0.15	1.81*	**Yes**
Type III Collision	No	**Yes**	1.46	3.06**	**Yes**
Total Collisions	No	**Yes**	1.75	3.01**	**Yes**
Trial Completion Time	No	**Yes**	0.14	1.98*	**Yes**

* *p*<0.05

** *p*<0.01

Table 8-5: Descriptive Statistics (Subject B)

	Baseline(Hand)				Intervention (DSS)			
Variable	Mean	SD	Min	Max	Mean	SD	Min	Max
Type I Collision	0.50	0.84	0.00	2.00	0.33	0..71	0.00	2.00
Type II Collision	1.33	0.82	0.00	2.00	0.00	0.00	0.00	0.00
Type III Collision	1.83	1.47	0.00	4.00	0.00	0.00	0.00	0.00
Total Collisions	3.67	2.16	1.00	6.00	0.33	0.71	0.00	2.00
Trial Completion Time	55.67	13.11	45.00	78.00	89.78	23.27	52.00	128.00



	Type I Collisions	Type II Collisions	Type III Collisions		Total Collisions
Hand	0.50	1.33	1.83		3.67
DSS	0.33	0.00	0.00		0.33

Figure 8-14: Collisions (Subject B)

8.6.2.1 Type I Collisions

The mean number of Type I collisions per trial in the intervention phase (M = 0.33, SD = 0.71) was lower than the mean number of Type I collisions per trial in the baseline phase (M= 0.50, SD = 0.84).

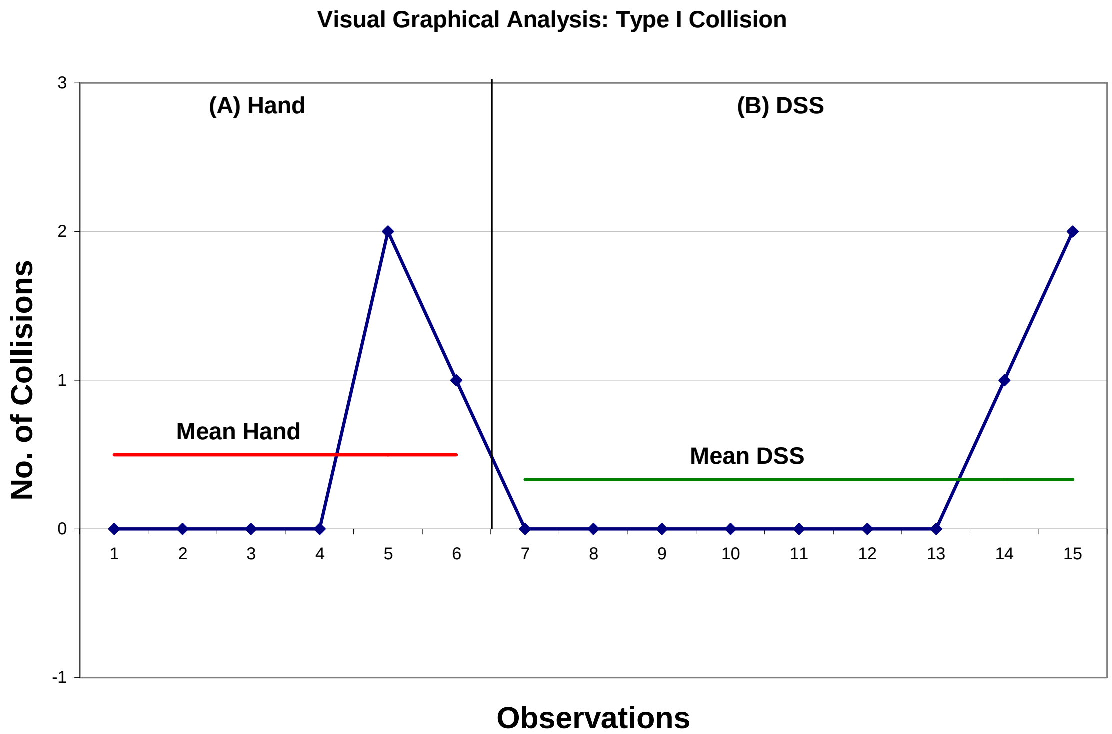


Figure 8-15: Number of Type I Collisions per Trial (Subject B)

During baseline 3 of 6 points were below the Celeration line while during the intervention phase all the observations were below the Celeration line (see Figure 8-16). According to the Bloom probability table, this difference in proportions indicated that there was a significant effect of intervention in reducing the number of Type I collisions ($p<0.05$).

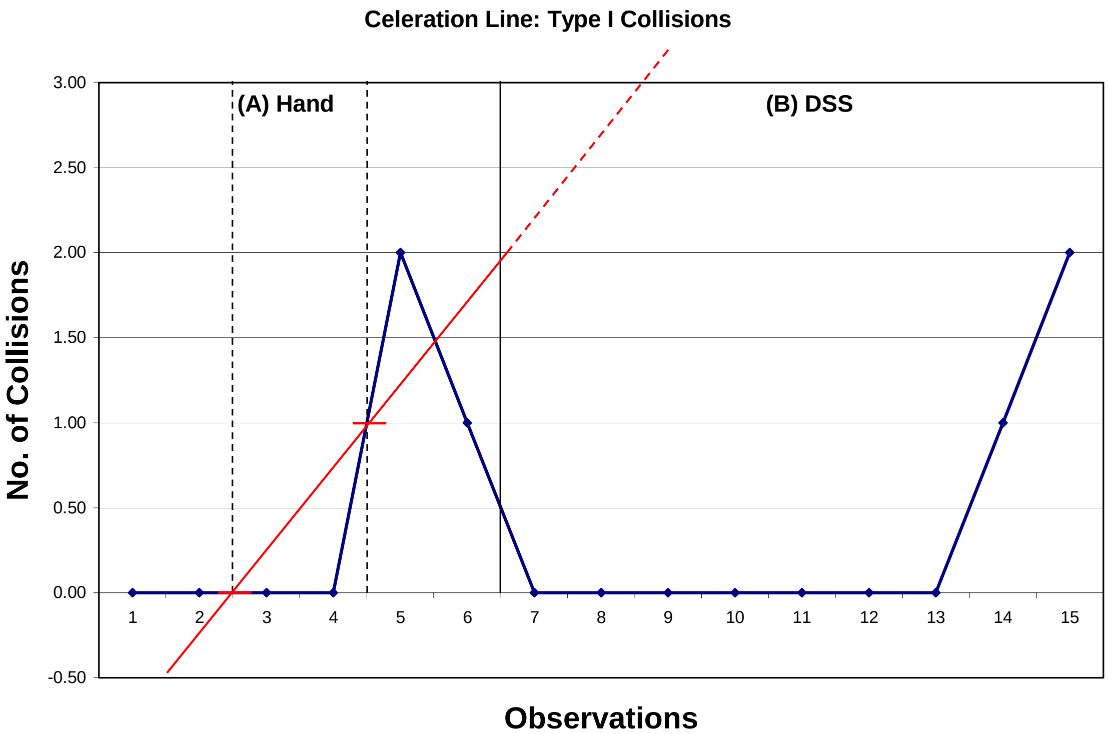


Figure 8-16: Celeration Line for Type I Collision (Subject B)

The C Statistic method indicated no significant trend in the baseline data of Type I collisions. The C Statistic method on the combined baseline and intervention data indicated that effect of the DSS on reducing the Type I collisions was statistically significant ($z=1.97$, $p= 0.024$).

8.6.2.2 Type II Collisions

The mean number of Type II collisions per trial in the intervention phase ($M = 0$, $SD = 0$) was lower than the mean number of Type II collisions per trial in the baseline phase ($M= 1.33$, $SD = 0.82$).

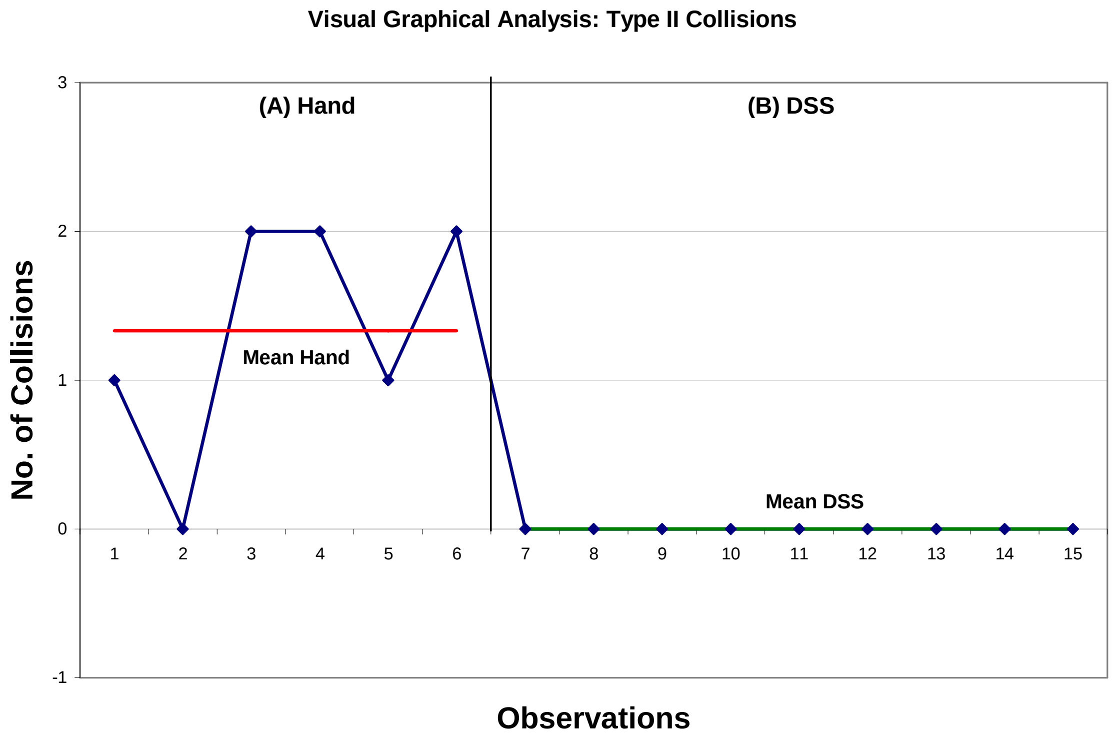


Figure 8-17: Number of Type II Collisions per Trial (Subject B)

During the baseline phase 3 of 6 points were below the Celeration line while during the intervention phase all the observations were below the Celeration line (see Figure 8-18). According to the Bloom probability table, this difference in proportions indicated that there was significant effect of intervention in reducing the number of Type II collisions ($p<0.05$).

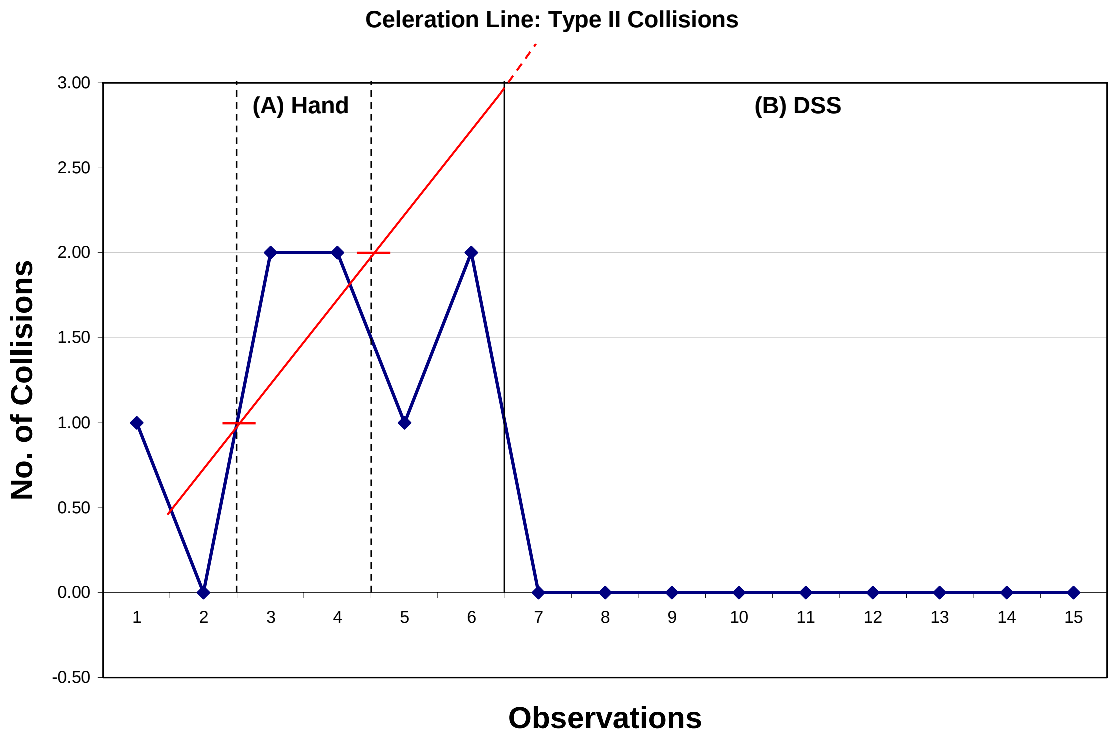


Figure 8-18: Celeration Line for Type II Collision (Subject B)

The C Statistic method indicated no significant trend in the number of Type II collisions during baseline. The C Statistic method on the combined baseline and intervention data indicated that effect of the DSS on reducing the Type II collisions was statistically significant (z = 1.81, p = 0.035).

8.6.2.3 Type III Collisions

The mean number of Type III collisions per trial in the intervention (M = 0, SD = 0) phase was lower than the mean of Type III collisions per trial in the baseline phase (M = 1.83, SD = 1.47).

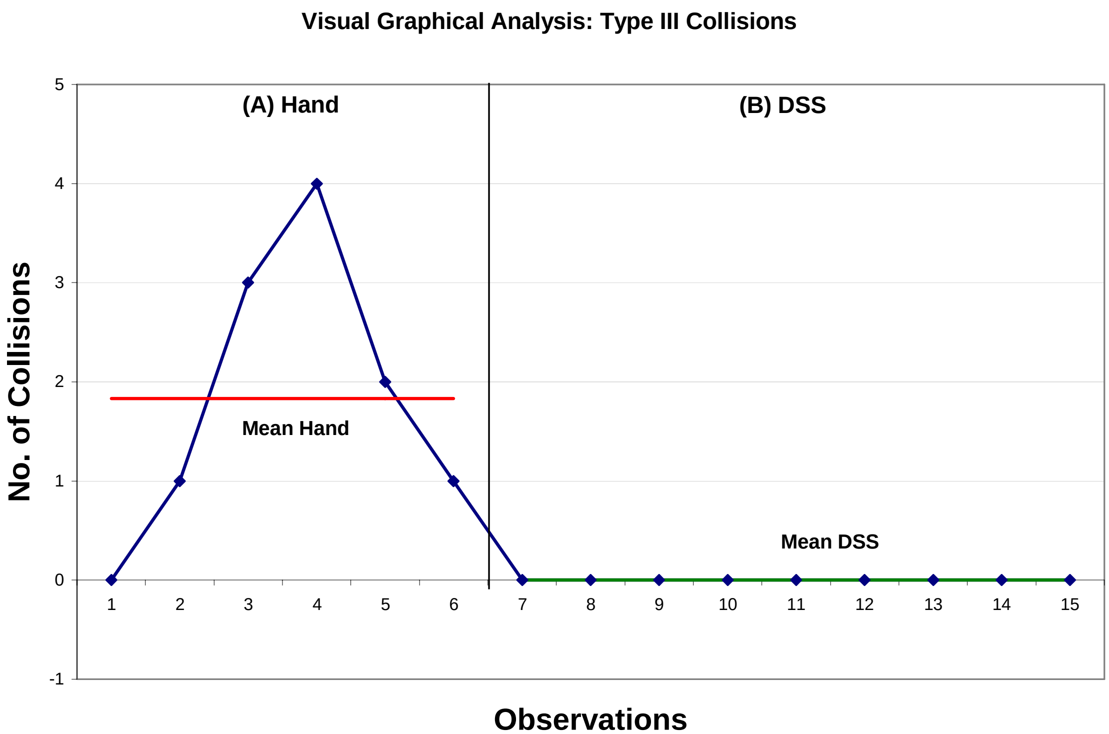


Figure 8-19: Graphical Method for Type III Collisions (Subject B)

During baseline phase 3 of 6 points were below the Celeration line while during intervention phase all the observations were below the Celeration line (see Figure 8-20). According to the Bloom probability table, this difference in proportions indicated that there was a significant effect of intervention in reducing the number of Type III collisions ($p<0.05$).

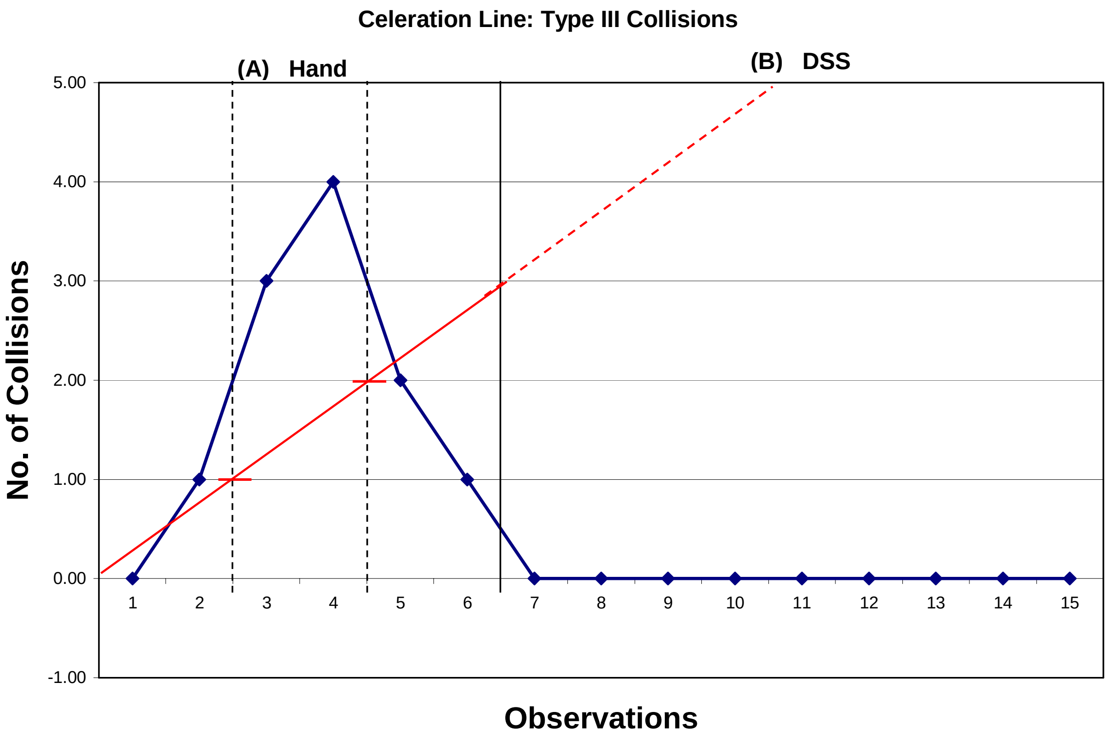


Figure 8-20: Celeration Line for Type III Collisions (Subject B)

The C Statistic method indicated no significant trend in the number of Type III collisions during baseline. The C Statistic method on the combined baseline and intervention data indicated that the effect of the DSS on reducing the Type III collisions was statistically significant ($z = 3.06$, $p = 0.0011$).

8.6.2.4 Total Collisions

The mean number of total collisions per trial in the intervention phase ($M = 0.33$, $SD = 0.71$) was lower than the mean number of total collisions per trial in the baseline phase ($M = 3.67$, $SD = 2.16$).

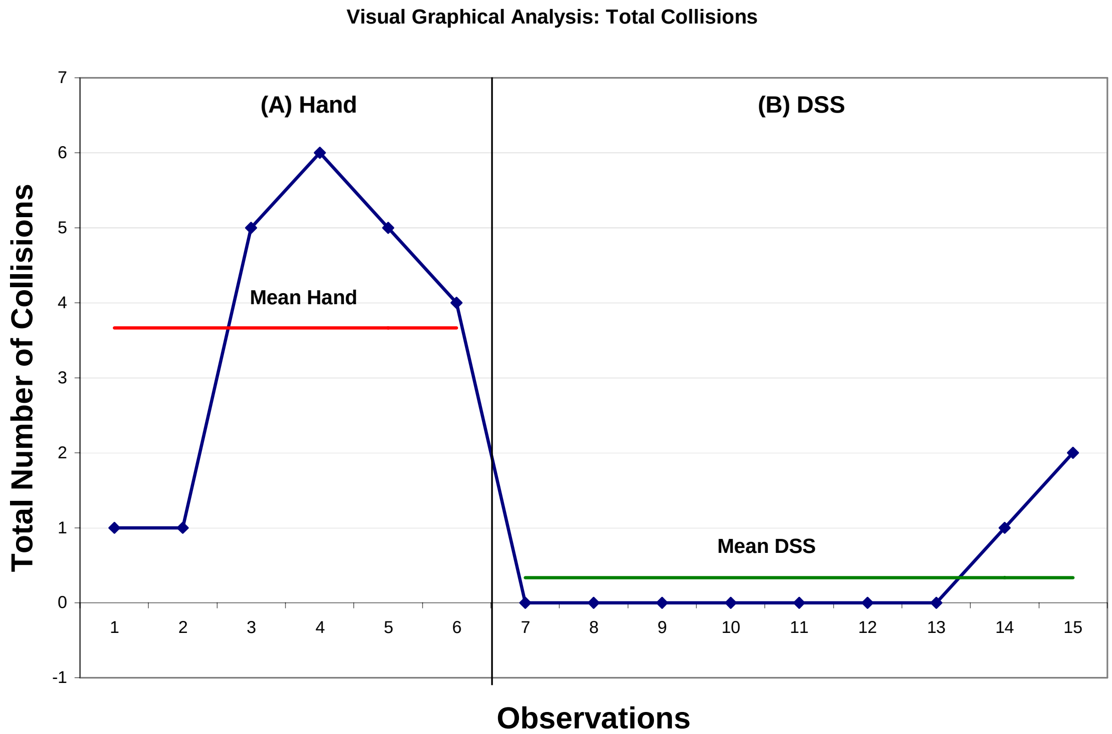


Figure 8-21: Graphical Method for Total Collisions (Subject B)

During baseline phase 2 of 6 points were below the Celeration line while during the intervention phase all the observations were above the Celeration line (see Figure 8-22). According to the Bloom probability table, this difference in proportions indicated that there was a significant effect of intervention in reducing the total number collisions (p>0.05).

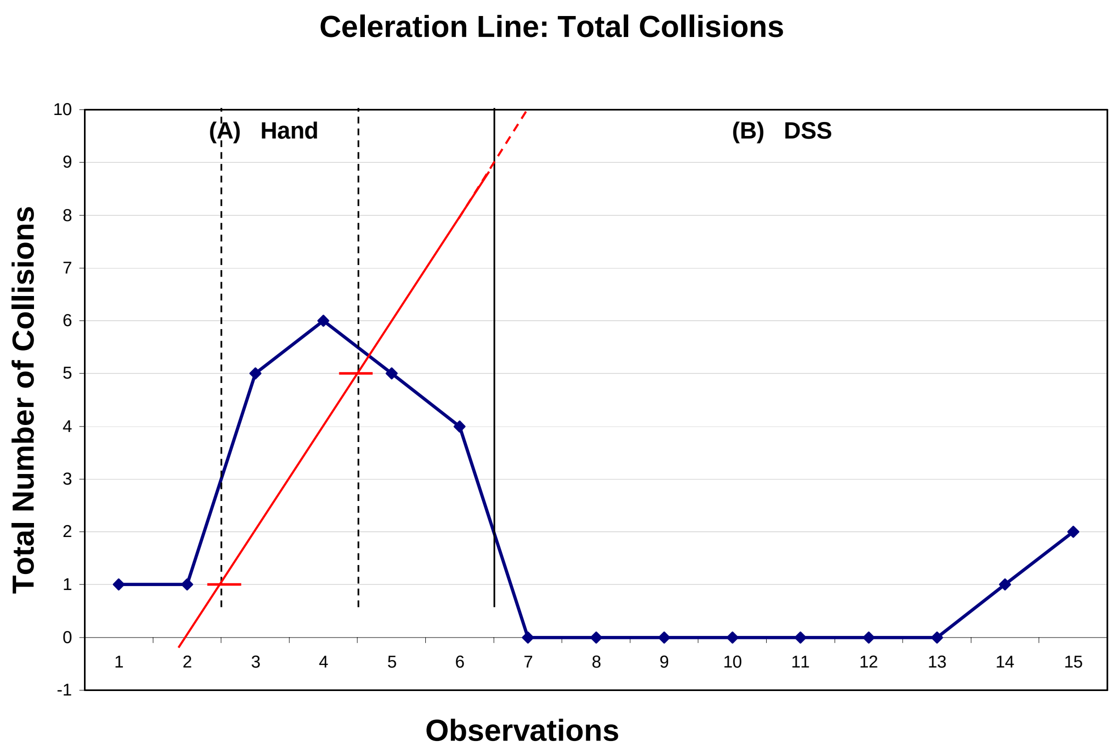


Figure 8-22: Celeration Line for Total Collisions (Subject B)

The C Statistic method indicated no significant trend in the total number of collisions during baseline. The C Statistic method on the combined baseline and intervention data indicated that the effect of the DSS on reducing the total number of collisions was significant ($z = 3.01$, $p = 0.04$).

8.6.2.5 Trial Completion Time

The average time to complete a trial in the intervention phase (M = 101.50, SD = 34.84) was higher than the average time to complete a trial in the baseline phase (M = 73.11, SD = 14.88).

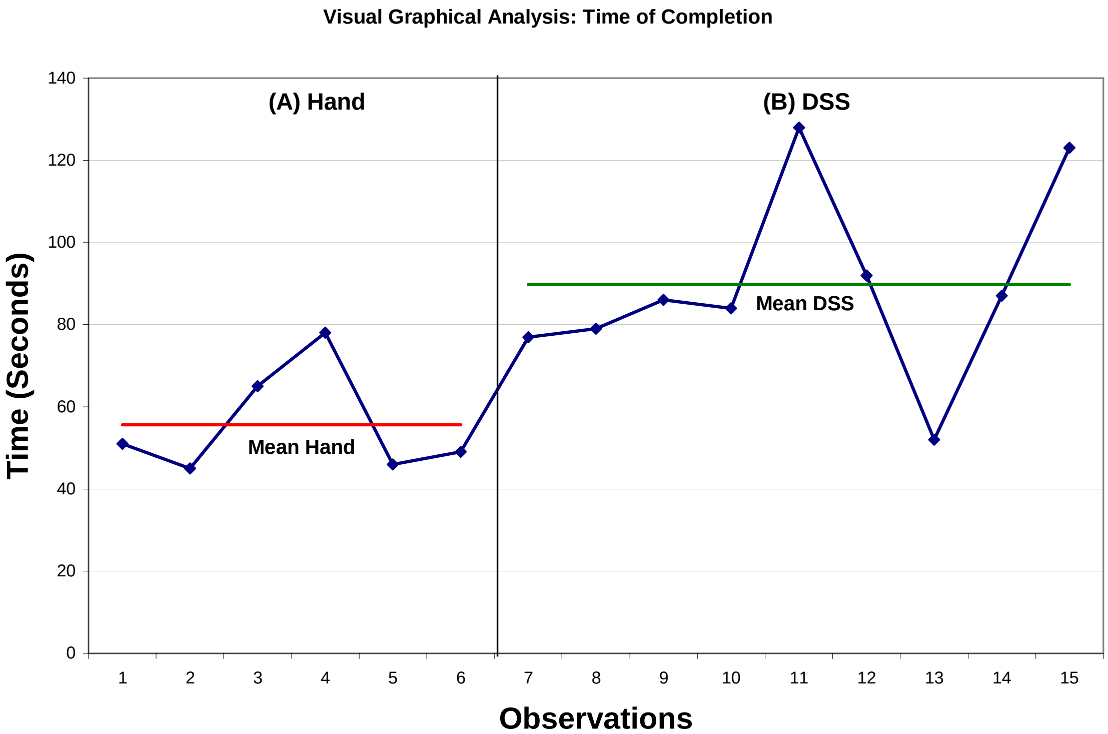


Figure 8-23: Graphical Method for Trial Completion Time (Subject B)

During baseline phase 3 of 6 points were above the Celeration line while during the intervention phase 9 of 9 points were above the Celeration line (see Figure 8-24). According to the Bloom probability table, this difference in proportions indicated that there was a significant effect of intervention in increasing the time to finish a trial ($p<0.05$).

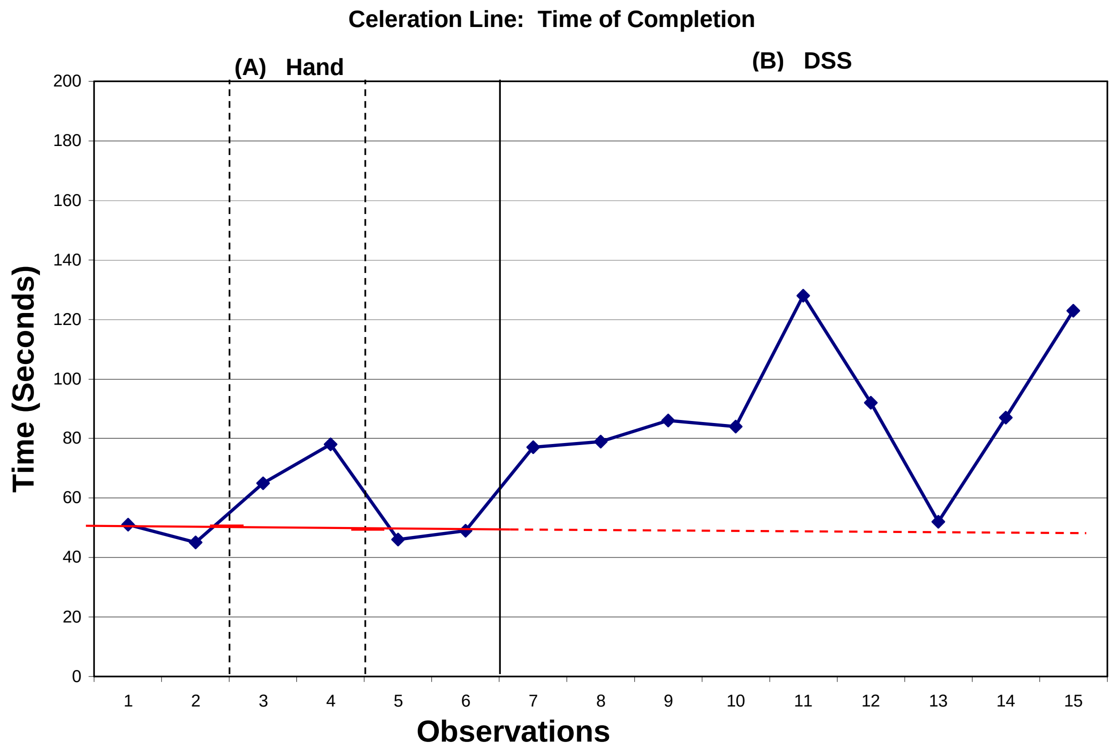
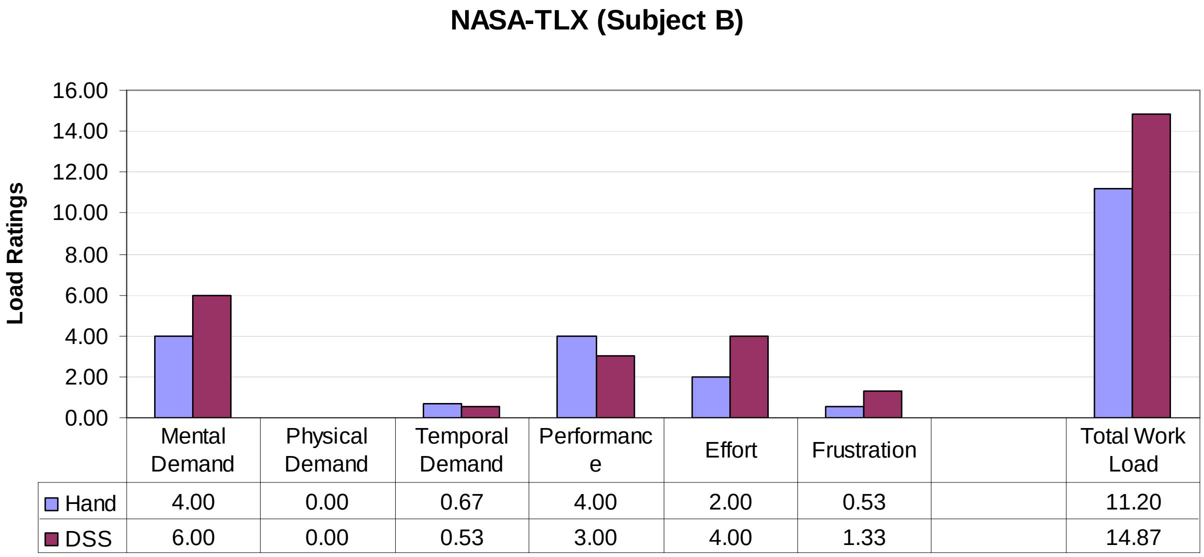


Figure 8-24: Celeration Line for Trial Completion Time (Subject B)

The C Statistic method indicated no significant trend in the Trial Completion Time during baseline. The C Statistic method on the combined baseline and intervention data indicated that use of the DSS significantly increased the Trial Completion Time ($z = 1.98$, $p = 0.022$).

8.6.2.6 NASA-TLX

Total Workload (TWL) with the DSS was higher in comparison to baseline TWL (see Figure 8-25). Mental demand, Effort, and Frustration with the DSS was higher in comparison to the baseline. On the other hand, Temporal demand and Physical demand was lower with the DSS. Subject B reported her own performance was better with the DSS in comparison to using her hand in baseline condition.



	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration		Total Work Load
Hand	4.00	0.00	0.67	4.00	2.00	0.53		11.20
DSS	6.00	0.00	0.53	3.00	4.00	1.33		14.87

Figure 8-25: NASA-TLX Scores

8.6.2.7 Matching People with Technology (Subject B)

Subject B compared suitability of the DSS to her current navigation method using MPT questionnaire. The DSS scored 42 points while her existing method scored 36 points on the MPT scale. She reported that using the DSS would improve her quality of life and she would have the stamina to use this device without stress or discomfort.

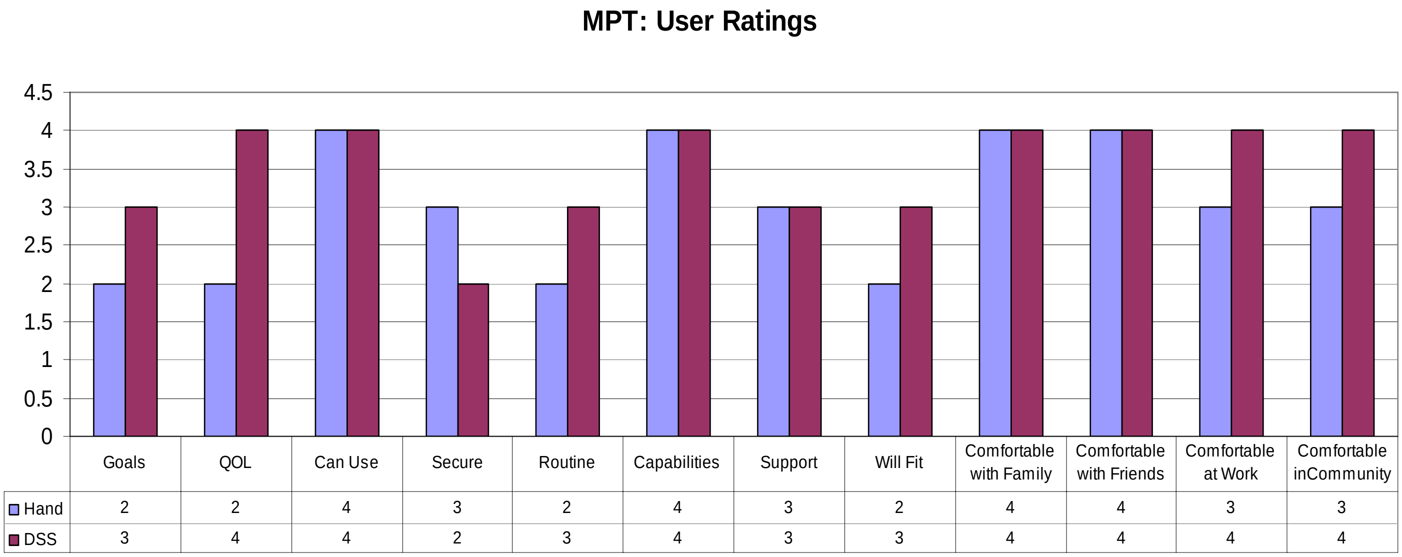


Figure 8-26: MPT Scores (Subject B)

8.7 DISCUSSIONS

The results of the Celeration line analyses are not considered reliable because of the very high variability in the baseline data. This high variability in the baseline data was related to the degree of difficulty in the obstacle courses. Participants found some of the obstacle courses relatively easy to navigate and had very few collisions while some obstacle courses were tough for the participants to navigate and they had more collisions in these obstacle courses when using cane. The effect on any dependent variable is considered significant if either the Celeration Line or the Tryon's C-Statistic test shows a significant effect.

8.7.1 Collisions

We hypothesized that using the DSS would reduce the occurrence of all types of collisions. Our hypothesis was based on that fact that the DSS will slow down the wheelchair whenever it is moving towards an obstacle, and the change in speed would cue subjects to steer around obstacles. Further, if a subject can not steer the wheelchair away from the obstacles the DSS will stop the wheelchair once it reaches a threshold distance from the obstacle. The results indicate that, for both subjects, the DSS significantly reduced the occurrence of collisions (Type I, Type II, and Type III). Further, only Type I collisions occurred when using the DSS but collisions of all types occurred under the baseline condition.

There were several causes of the collisions that occurred during the baseline phase. Both subjects had difficulty coordinating the speed with which they scanned the environment (either with the cane or by hand) and the wheelchair's speed. In addition, both subjects occasionally responded too slowly to obstacles that they did detect. Finally, both subjects may not have had an adequate understanding of the wheelchair's size and dynamics, as the dynamics and size of the wheelchair used in experiment were different than the subjects' own wheelchairs. An additional cause of collisions for subject B was that she had limited reach with her hand and could not detect obstacles on the right side of the wheelchair.

8.7.2 Trial Completion Time:

For both subjects, the average Trial Completion Time when using the DSS was higher than baseline, but the difference was only statistically significant for Subject B. However, for both participants, this performance was achieved at the expense of hitting significantly more obstacles.

8.7.3 NASA-TLX

Subject A felt less TWL with the DSS in comparison to using the cane because it reduced her effort and made her feel less frustrated. Subject A did not have the stamina and endurance required to use the cane efficiently, which resulted in more collisions, poor performance and increased frustration. Subject B, on the other hand, felt more TWL with the DSS because she found learning to use new technology in a short period of time challenging, so she felt more mental demand and she had to put more mental effort into each trial. In addition, she felt less physical demand and exertion in the baseline condition as she was using her hand for navigation.

Unfamiliarity with the DSS and the difficulty of learning to use a new technology in a short period of time made the use of the DSS more mentally demanding for both subjects. Further, the auditory feedback from the DSS was not intuitive and informative enough for subjects to locate obstacles so they had to make multiple maneuvers to drive the wheelchair around them. Both subjects took more time on average to finish each trial when using the DSS but reported less temporal demand because she did not have full control of the speed of the wheelchair.

Subject B was able to navigate effectively in the experimental setting using her hand, because all obstacles were tall enough (five feet) that she could sense them with her hand. However, in real world settings with lower height obstacles she won’t be able to sense the obstacles, which could result in personal injury and property damage. She has restricted use of her wheelchair at home because of regular occurrences of collisions.

8.7.4 MPT

Both subjects reported higher scores on MPT with the DSS, which shows that both subjects felt that the DSS is a better way of navigation than their existing navigation methods (cane and hand). Both subjects felt that they would develop a better understanding of the DSS with more usage and that they would be able to learn to maneuver the chair around obstacles more efficiently. Both subjects felt that they had the physical and mental strength, stamina, and endurance required to use the DSS. Both subjects felt that obstacle avoidance behavior would improve their quality of life and would encourage them to visit places alone. Both participants felt that they would feel more secure and less stressed when using the DSS because they would not have to constantly worry about collisions which could result in injury or property damage. Both participants reported that they would feel confident and not self conscious with the DSS in home, work and community settings. Both subjects felt that their current living environment might not be supportive for the use of the DSS because they live in apartments in which the door widths are not compliant with ADA guidelines.

8.8 LIMITATIONS

A Single Subject Design conducted in a single session limits the generalizability of the results. The next study should be longitudinal, and other populations that may benefit from DSS should be included.

The present hardware, seating and positioning, and time limit of the study did not allow testing of subject populations with advanced seating and positioning needs, and people with cognitive deficits. Two recruited subjects, one with complex seating and positioning needs and second with cognitive impairments, could not finish the protocol because of these limitations. One subject required switched joystick input which the current DSS prototype could not support. The second subject had cognitive deficits and had no previous experience driving a powered wheelchair, so she could not learn to maneuver the joystick because of her inability to relate the joystick movement and the movement of the wheelchair. These subjects can be accommodated in a powered wheelchair with the help of the DSS if the wheelchair had option of accommodating the more advanced seating and positioning and the study allowed for multiple sessions for each subject.

The experimental wheelchair was different from the wheelchairs participants used on day to day basis, which may have affected participants' performance when using their existing navigation techniques (cane or hand). The next phase of study should be performed by mounting the DSS hardware on the subjects' wheelchair, and comparisons should be made between their existing navigation methods and the DSS.

8.9 CONCLUSIONS

Evaluation of the DSS with Subject A and Subject B shows the merits of the DSS for people with visual and mobility impairments. The DSS reduced Type 1, Type II, and Type III collisions significantly, at the expense of increased time for the task completion.

Subject A experienced less Total Workload when using the DSS in comparison to using the cane, but subject B felt more workload when using the DSS in comparison to using their hand. Subjects reported that when using the DSS they experienced less physical demand, less temporal demand, but more mental demand in comparison to using the cane or their hand. Subjects when evaluating their own performance reported better performance when using the DSS. Further, subjects had to put less effort to achieve that level of performance and they felt less frustrated while using the DSS. When asked the suitability of the DSS system for their long term use subjects reported they will prefer the DSS over their current navigation assistance devices.

9.0 SUMMARY AND RECOMMENDATIONS

9.1 CONCLUSIONS

The purpose of this research was to design and evaluate a clinically and commercially viable smart wheelchair architecture, which may facilitate independent mobility for individuals with a broad spectrum of disabilities. Several hypotheses were proposed related to the performance of the DSS and evaluation of the DSS by the user population on various navigation tasks. The main focus of this dissertation was to determine if the DSS provides effective independent mobility to people with visual and mobility impairments.

The DSS architecture was able to provide reliable sensor coverage. The modified sensor coverage area of the Pride wheelchair was able to provide coverage on the left and right side of the wheelchair, which facilitated doorway passing and wall following modes. There were a few blind spots in the modified sensor coverage in sector 7 and sector 8 around the wheelchair, but these were due to the manufacturing artifacts in the rear sensor node shell.

The mounting of the DSS components did not restrict the ability of the wheelchair driver to transfer into and out of the wheelchair. Two-piece magnetically clamped front bumpers and the sensor node mountings were positioned in such a way that the wheelchair operator can transfer in and out of the wheelchair from the front side by opening the foot rests, just as they would in the absence of these mountings. To transfer from the side, the network cable from the side sensor node needs to be unplugged before removing the armrests. After completion of the transfer, the armrests and the network can be plugged in again and the DSS is ready to use.

The maximum safe speed with the DSS was 2.6 miles/hour (4.16 km/hr) which is comparable to the average speed at which powered wheelchair users drive their wheelchair during day to day activities (1.8 miles/hour) [59]. The effective speed of the DSS in real-world situations with the intended population is expected to be less than 2.6 miles/hour because the wheelchair will slow down in the presence of the obstacles.

Adding the DSS hardware to the underlying powered wheelchair did not affect the range of travel or the battery life. When in operation, the DSS is expected to consume from 16 to 27 watts, which will reduce the distance the wheelchair can travel by approximately 3%, based on standard 12 volt/60 amp-hour batteries. When the DSS is not in use, the DSS architecture will be asleep and will consume less than 1 watt.

Adding the DSS hardware to the underlying wheelchair increased the width of the wheelchair by 4 inches and the length by 5.5 inches. These increased dimensions can restrict the user from passing through narrow doorways, traversing narrow corridors, turning in narrow spaces, and reaching certain objects such as water fountains, light switches, elevator switches, toilet seats, and faucets.

The DSS was able to follow walls safely at a distance of 6 inches without being stopped by the walls. The minimum door width the DSS was able to pass through was 30 inches. Changing the mounting of the side sensor nodes may decrease the overall width of the wheelchair and the wheelchair may be able to follow the walls closer and pass through narrower doorways.

Hypothesis Q1. People will have fewer collisions when using the DSS than when using a cane.

This hypothesis was accepted because results from all five studies showed that upon using the DSS alone or along with the cane, participants were able to reduce the number of collisions significantly in comparison to using the cane alone. The collisions that occurred when using the DSS were of very low severity (Type I collisions) which were caused by inappropriate stop thresholds programmed in the software. Sensor stop thresholds were programmed before installing the bumpers, which may be one reason why the bumpers came in contact with the obstacles and displaced them. The bumpers were not activated by the cardboard obstacles when the DSS was active, but provided extra safety to the user in the absence of the DSS.

Hypothesis Q2. The average time of completion for navigation tasks will be greater when using the DSS in comparison to using a cane.

For participants in studies 1, 2, and 4 there was not a significant differences in the time of task completion between the cane alone and the DSS alone. When using the cane along with the DSS, the task completion time was significantly higher in comparison to the cane alone. For O&M specialists, the task completion time for DSS alone and DSS along with the cane was significantly higher in comparison to using the cane alone. Participants with visual and mobility impairments took significantly more time when using the DSS alone in comparison to using the cane alone. However, low task completion time when using the cane was achieved at the expense of more collisions.

Holliday et al. conducted a survey of users of wheelchairs (N= 52) and health care professionals and others (N=89) to determine the relative importance of five aspects of wheelchair maneuverability [57]. The 30 powered wheelchair users in the survey prioritized these five factors as follows:

1. Avoiding collisions with walls/objects (Collisions)

2. Moving in small spaces (Moving)

3. Reaching an object (Reach)

4. Time to complete a task (Time)

5. Reducing the need to drive backwards (Backward).

For wheelchair users, avoiding collisions was the most important factor and time to complete a task was ranked lower. So even though time for task completion was low when using the cane alone, it is likely that using DSS for navigation will provide a more satisfying user experience due to the decrease in collisions. Similarly, choices and priorities of health care professionals in the survey also tend to agree with the choices made by the powered wheelchair users in the survey.

Hypothesis S1. Perceived physical demand in a given navigation task will be lower when using the DSS than when using a cane.

This hypothesis was confirmed because in all studies participants reported significantly less physical demand when using the DSS alone or along with the cane in comparison to using the cane alone. The physical demand when using the cane alone was caused by the need for continuous scanning for obstacles. Non-ambulatory visually-impaired individuals with limited physical strength (e.g. aging, MS, CP) might find the use of the cane extremely difficult because of the fatigue it produces. Physical demand when using the DSS was very low, and mainly caused by the continuous maneuvering of the joystick.

Hypothesis S2. Perceived mental demand will be higher when using the DSS than when using a cane.

This hypothesis was not supported in study 1, study 2, and study 4, as participants in these studies reported no significant difference in mental demand when using the DSS versus the cane. On the other hand, this hypothesis was supported in study 3 with O&M specialists, as they reported more mental demand when using the DSS in comparison to using the cane. Similarly, both participants in study 5 reported more mental demand when using the DSS in comparison to using the cane alone or their hand.

A likely source of mental demand under all conditions was the need to construct and maintain a mental map of the test environment (the target, surrounding obstacles, the position and orientation of the wheelchair). Mental demand when using the cane alone resulted from the need to coordinate scanning and driving. This was difficult for participants because they had to use both their hands and most of the participants were not ambidextrous. Mental demand would also be expected to decrease over time as they learn to coordinate scanning and driving. Mental demand when using DSS was caused when participants had to estimate the position and sizes of obstacles based on auditory feedback from the wheelchair and then use this information to maneuver the wheelchair around obstacles and move towards the sound target. In addition, crosstalk between ultrasound sensors could cause the wheelchair to act in ways that confused participants requiring them to work extra hard mentally to reach to the target.

O&M participants were experienced cane users so they were able to coordinate the scanning and the driving blindfolded when using the cane alone. On the other hand when using the DSS, they had trouble locating obstacles and steering the wheelchair around them based on auditory feedback from the DSS.

Hypothesis S3. Frustration when using the DSS will be lower than when using a cane.

This hypothesis was supported in study 1 and study 2, where participants reported significantly less frustration when using the DSS alone in comparison to using the cane alone.

This hypothesis was not supported in study 3 and study 4. In study 3, participants did not experience a difference in frustration level when using the DSS alone compared to when using the cane alone. On the other hand, participants in study 3 experienced more frustration with the DSS in comparison to the participants in study 4, but the difference did not reach on the statistical significant level because of the small sample size. O&M specialists in study 3 experienced more frustration when using the DSS alone in comparison to using the cane alone but surprisingly reported less frustration when using the DSS along with the cane in comparison to the cane alone. Participants with visual and mobility impairments did not feel much frustration in either condition.

Using the cane caused frustration because participants felt insecure about hitting obstacles and even after trying hard they could not stop the collisions when using the cane alone. Frustration with the DSS was mainly caused by the repeated maneuvers required to steer the wheelchair around the obstacles, but these maneuvers were decreased as participants learned to use the DSS. False positive stops because of the sensor noise perplexed participants and it caused frustration and confusion. It should be noted, however, that frustration was still low under both the conditions so it is unclear whether frustration was actually problematic.

Hypothesis S4. Perceived effort when using the DSS will be lower than when using a cane.

This hypothesis was supported in study 1 and study 2, as participants in these studies reported significantly more effort with the cane alone. On the other hand, this hypothesis was not supported in study 3 and in study 4, as participants reported less effort when using the DSS but this difference did not reach significance owing to the small sample sizes in both studies. Participant A in study 5 reported less effort when using the DSS and participant B reported more perceived effort with the DSS than in the baseline condition. One of the reasons participant B did not feel the difference in the perceived effort was because she used her hand instead of the cane in the baseline condition so her physical effort was not reduced.

Hypothesis S5. TWL when using the DSS will be lower than when using a cane.

This hypothesis was supported in study 1 and study 2, as participants in these studies reported significantly less TWL when using the DSS in comparison to using the cane alone. On the other hand, this hypothesis was not supported in study 3 and in study 4. Participants in study 3 and study 4 reported less TWL when using the DSS but this difference did not reach a significant level because of the small sample sizes in both studies.

TWL for participant A in study 5 was lower when using the DSS in comparison to using the cane. On the other hand, TWL for participant B was higher with the intervention (DSS) in comparison to the baseline when she was using her own hand to scan. Participant B experienced low TWL in the baseline because not using the cane in the baseline significantly reduced the physical demand, frustration, and physical effort which otherwise would have created more fatigue because of her MS.

Both participants in study 4 and study 5 gave higher scores to the DSS in comparison to the cane as a preferred navigation assistance method on the MPT questionnaire. The highest priority for most participants was avoiding collisions, which is why participants identified the DSS as the best navigation assistance method for their day-to-day activities in spite of the high temporal demand and high task completion time. Participants reported that they would prefer to use the DSS at home, work, and in the community in comparison to the cane. Both participants in study 5 were able to learn to drive the wheelchair with navigation assistance from the DSS without any difficulty, which shows the promise of the DSS as a navigation assistance tool even for people with mild cognitive impairments.

The safety of the wheelchair driver and safety of the environment are key factors that clinicians and rehab practitioners consider when prescribing powered mobility for people with disabilities. The DSS's performance in avoiding collisions without significantly increasing task completion time presents it as an encouraging intervention. Many researchers are working on smart wheelchairs, and the decreasing costs of sensors and computing costs imply that the goal of a commercially viable and clinically proven solution is close to realization.

9.2 LIMITATIONS & FUTURE WORK

All studies reported in the present research were conducted in a controlled laboratory environment, which does not represent the real world scenarios that people with disabilities encounter in their day-to-day lives. Ultimately, the value of the DSS will be determined by its performance with the target population in the real world. Therefore, for higher ecological validity, the evaluation process should include “field trials” in which the DSS is used by target users for extended periods of time outside of the laboratory environment. Field trials should be performed after the suggested modifications in the DSS architecture are implemented. One purpose of field trials is to compensate for the limitations of the lab trials, which must be conducted in a controlled environment. Another advantage of field trials is that users will be able to experience the DSS for several hours and will provide valuable feedback regarding the performance of the DSS in unconstrained environments. Investigators involved in the evaluation of the DSS in real world settings should also evaluate the users’ ability to function when using the navigation assistance from the DSS using instruments such as Functioning Everyday With a Wheelchair (FEW) [66, 67] or Power Mobility Indoor/Community Driving Assessment (PIDA) [56, 68]. Further, anecdotal data obtained during the interviews will provide investigators with additional insight into specific situations that lead to system failures (collisions or software crashes), difficulties encountered when transporting the system, and problems positioning users within the chair.

When an individual obtains a new powered wheelchair, he or she often purchases the wheelchair through a clinician, who is responsible for configuring the wheelchair (e.g., input method, maximum velocity, and maximum acceleration), selecting seating and positioning hardware (e.g., cushions, lateral supports, and head rests), and mounting other equipment on the wheelchair (e.g., communication devices, lap trays, and ventilators). The assessment process typically involves reviewing the client's medical history, measuring the client's flexibility and range of motion, assessing the perceptual, motor, and cognitive skills required to operate a powered wheelchair, interviewing the client and caregivers, and, ultimately, some experimentation to identify a system that best meets the client's needs.

Future evaluation of the DSS should involve occupational therapists, rehabilitation technologists and wheelchair suppliers who provide wheelchair seating and mobility services. These participants should complete mock powered mobility assessments involving the DSS to evaluate the system's ability to coexist with standard seating and positioning hardware. The trials will also provide insight into the training and documentation that clinicians will need to effectively utilize the DSS in practice. The mock powered mobility assessments will be used to evaluate the effectiveness of the instructional materials and configuration software of the DSS.

Commercialization of the DSS cannot be completed without comprehensive engineering tests based on ANSI-RESNA wheelchair standards. This evaluation should include the following tests:

1. Climatic conditioning: Climatic conditioning tests should be performed to test the functioning of the DSS architecture in extreme weather conditions.
2. Power and control systems testing: The main intention of these tests is to ensure that the electronics and batteries operate in a safe manner under all types of circumstances (e.g. depleted batteries, short circuit).
3. Impact and fatigue strength: To insure the robustness of the mountings and hardware in extreme driving conditions.

4. Electromagnetic Compatibility (EMC): The DSS architecture is a distributed, embedded architecture, which can have problems with electromagnetic interference (EMI). EMI consists of any unwanted, spurious, conducted (voltages or currents) or radiated (electric or magnetic fields) signals of electrical origin that can cause malfunctioning or degradation in the performance of the DSS. Because of these problems, all components of the DSS (sensor nodes and translator node) must comply with specifications to ensure electromagnetic compatibility (EMC).

Functional and independent mobility in children with disabilities and developmental delays has been shown to improve cognitive, social, and perceptual skills. Further, independent mobility can reduce learned helplessness and increase participation with peers in everyday activities [11, 23]. Many investigators have shown smart wheelchairs to be an important tool for teaching powered mobility to such children from a very young age [23, 24, 47, 69]. Future evaluation of the DSS should be done with this population to teach them safe navigation skills.

Results from this study cannot be generalized for other intended population of the DSS because most of the participants recruited for this study (able-bodied, O&M, and people with visual impairments) were not disabled. Only two non-ambulatory visually impaired participants were recruited for this study because it was difficult to recruit participants from this population. Future evaluation of the DSS should be with participants from a more diverse population, e.g. aging, TBI, spastic CP. Potential candidates for the DSS also include those who were denied powered wheelchairs or have a history of unsafe driving and accidents.

Reliable operation of the DSS in unknown environments requires it to detect upright obstacles as well as drop-offs. Drop-offs are responsible for most disastrous and fatal injuries among wheelchair users [17, 18, 70]. The present architecture of the DSS does not provide any reliable solution for the detection of the drop-offs, which limits its operation to modified environments in which drop-offs have been eliminated. Future versions of the DSS should employ reliable drop-off detection technology and evaluate the user performance in environments which are not controlled.

The current hardware of the DSS can only support proportional joysticks. Because of this, many potential users of the DSS who required alternate input methods (e.g. switched input, sip-n-puff joystick, head operated joystick) could not participate in the study. Future versions of the DSS should have provisions for these alternate input devices so a more diverse subject population can be recruited.

Five foot high cylindrical tubes were used in this research as obstacles. The height and shape of these obstacles made them easy to be detected by sonar and IR sensors and this is likely to have enhanced the obstacle detection performance of the DSS. The next phase of trials should involve obstacles of varying height, shapes, colors, and surface textures, which will present varying level of detection difficulty for the proximity sensors.

The MPT was administered based on subjects' experiences in a controlled laboratory setting in short period of time, so most of the questions were answered based on hypothetical scenarios. For more reliable results, the MPT should be administered in real world settings, which would require long term use of the DSS in the homes of the users.

There are a significant number of individuals with disabilities who can benefit from the use of bumpers alone. Future evaluation of the DSS should be done with these individuals with only the bumpers active. Using only the bumpers will reduce the severity of collisions which otherwise would have hurt the user or caused property damage.

9.3 MODIFICATIONS TO DSS

The sensor coverage provided by the DSS architecture has blind spots and limited coverage in certain areas which can cause severe collisions that result in injury to the driver or property damage. These areas, particularly in the back of the wheelchair (sector 6, sector 7, sector 8 and sector 9), can be modified by changing the position and direction of certain URs in the back and right side sensor nodes.

The present positioning of the sensors in the sensor nodes was chosen to detect lower height, medium height, and overhead obstacles. The direction of certain URs in the rear, right side, and left side sensor nodes were too steep, so they were unable to detect any obstacles. These directions should be adjusted so they will be able to detect overhead obstacles.

Currently, the bumpers are mounted 7 in (17.78 cm) above the ground, so obstacles lower than 7 in (17.78 cm) can not be detected by the DSS bumpers, and can cause catastrophic collisions. Reducing the height of the bumpers will affect the underlying wheelchair's ability to climb inclines, so the height of the bumpers can not be reduced any further. More IRs in front of the wheelchair should be pointed such that they will be able to pick up obstacles of lower heights.

The URs used in the DSS have large detection cones, which creates uncertainty about the exact position of obstacles in each cone. This uncertainty can prevent the DSS from passing through doors, following a wall closely, or reaching certain objects. Future versions of the DSS should use URs with smaller detection cones, which will reduce the uncertainty in detecting the position of obstacles and will help in reducing sensor crosstalk.

The URs and IRs used in the DSS have minimum obstacle detection distances of 6 in (15.24 cm) and 8 in (20.32 cm), respectively. Obstacles at distances less than the minimum detection distance can not be detected reliably and can create false negative impressions about the presence of obstacles. Future versions of the DSS should explore the possibilities of URs and IRs which can reliably detect obstacles at shorter distances.

A few collisions that occurred with the DSS were because of the inappropriate stop thresholds programmed in certain sectors around the wheelchair. The stop threshold in these sectors should be adjusted so these collisions do not occur in the future. Note that these collisions occurred because the bumpers displaced the obstacles, and that without the bumpers these collisions would have not occurred.

The URs and IRs are sampled 5 times a second, and this low sampling rate limits the maximum safe speed that can be achieved with the DSS. The reason for the low sampling rate was the high detection range of the URs (254 in), which caused the ultrasound waves from each UR to remain in the air for a long time (38-45 milli seconds). Because of the longer duration of these waves in the air, sequential firing of the sensors in each sensor node was adopted and this resulted in the current sampling rate. Increasing the sensor sampling rate will increase the chances of sensor crosstalk. There are two ways to reduce the sensor crosstalk and increase the maximum safe speed of the wheelchair:

(a) Changing the firing pattern of the URs to minimize crosstalk

(b) Changing the URs to shorter range URs (Deventech SRF-10, SRF-08) which can be sampled at faster rate.

The DSS provides auditory feedback when the wheelchair is stopped by the DSS in the presence of an obstacle, whenever the bumpers are touched by an obstacle, and whenever the driver operates the wheelchair in override mode. Participants in this research relied on the auditory feedback to localize the position of the obstacles whenever the DSS stopped the movement of the wheelchair. Good and intuitive auditory feedback can help drivers locate the obstacles and steer the wheelchair around them, without the need for multiple joystick maneuvers.

Many participants in the study had difficulty locating the position of the obstacles based on the auditory feedback from the DSS. Whenever the wheelchair is stopped by an obstacle, the DSS can provide auditory feedback from five sensor nodes (only one sensor node at a time) to show the position of the obstacles in any of five directions (front right, front left, right, left, back). Feedback pattern from the sensor nodes were similar, so participants had difficulty determining which sensor node was providing the auditory feedback. Secondly, the sound of the feedback was not loud enough, so it was hard for participants to hear the feedback. Auditory feedback from the DSS can be improved in the following ways:

1. Instead of providing the same feedback pattern from all the sensor nodes, the feedback pattern should be different so the driver can locate obstacles reliably.
2. Using louder auditory feedback will make the beeping easier to hear.
3. Providing feedback whenever the wheelchair is approaching an obstacle, instead of when the wheelchair is stopped by the DSS, will help drivers understand the position of the obstacle and allow them to steer the wheelchair away from obstacles before coming to a stop. This behavior will help reduce the time of task completion and reduce the number of joystick maneuvers participants need to steer the wheelchair around obstacles.

Auditory feedback is not always the most desirable choice for many people with disabilities because :

1. Family members and other people might not feel comfortable with the continuous beeping from the DSS in cluttered environments
2. Many people with disabilities don't want to show their disability in public, and auditory feedback may attract unwanted attention.

Many participants suggested incorporating tactile feedback into the DSS. Tactile feedback will be more subtle and will not attract the attention of the public or family members but at the same time will be challenging to implement. Future version of the DSS should include tactile feedback so people with hearing impairments, which are common in the aging population, can benefit from the DSS.

Sensor node shells were mounted on the tubular section of the underlying wheelchair using the flex mounting hardware from PanaVise[7], which were not able to hold the sensor nodes firmly. As a result, the front sensor nodes could get stuck in the clothes of the user and their positions could get changed when users were getting in and out of the wheelchair. Future versions of the DSS should have mounting hardware which will hold the sensor nodes in a stable position so the performance of the DSS will not be affected. Having the sensor node mountings spring loaded will prevent possible damage to sensor nodes when they are hit by the user when transferring in and out of the wheelchair or by the obstacles when the DSS is operating in the override mode or when obstacle could not be detected by the sensor coverage field.

URs in the right side and left side sensor nodes were positioned such that users' hands blocked the sensors and triggered the stop threshold. In future versions of the DSS the sensor nodes

[7] PanaVise Products, Inc., Reno, Neveda

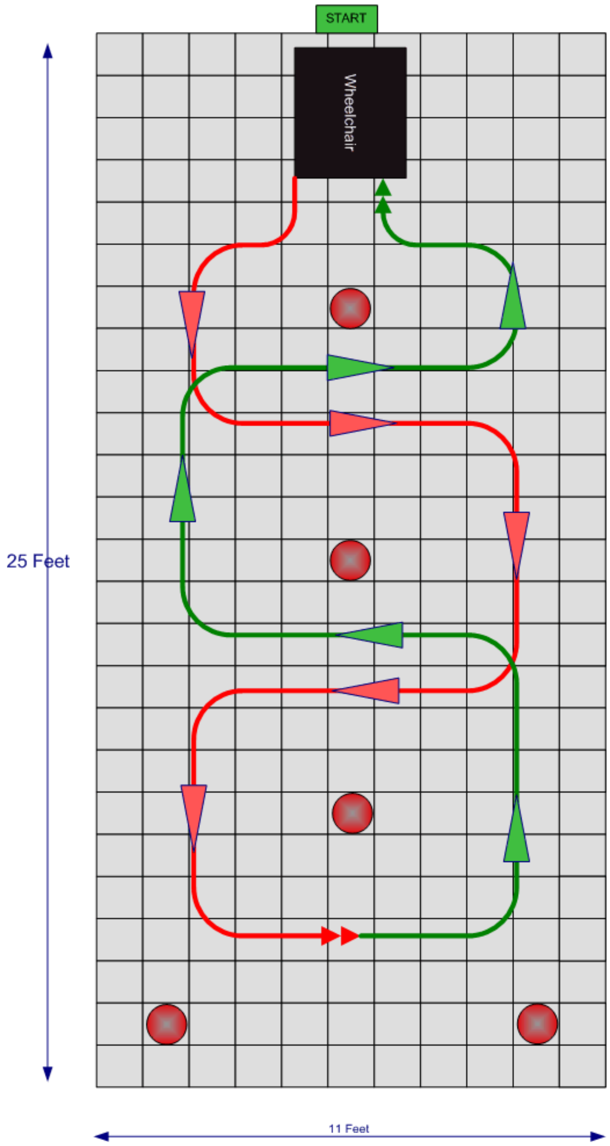
should mount in such a way that sensors will not get triggered by the user's hand, clothes, or other body parts.

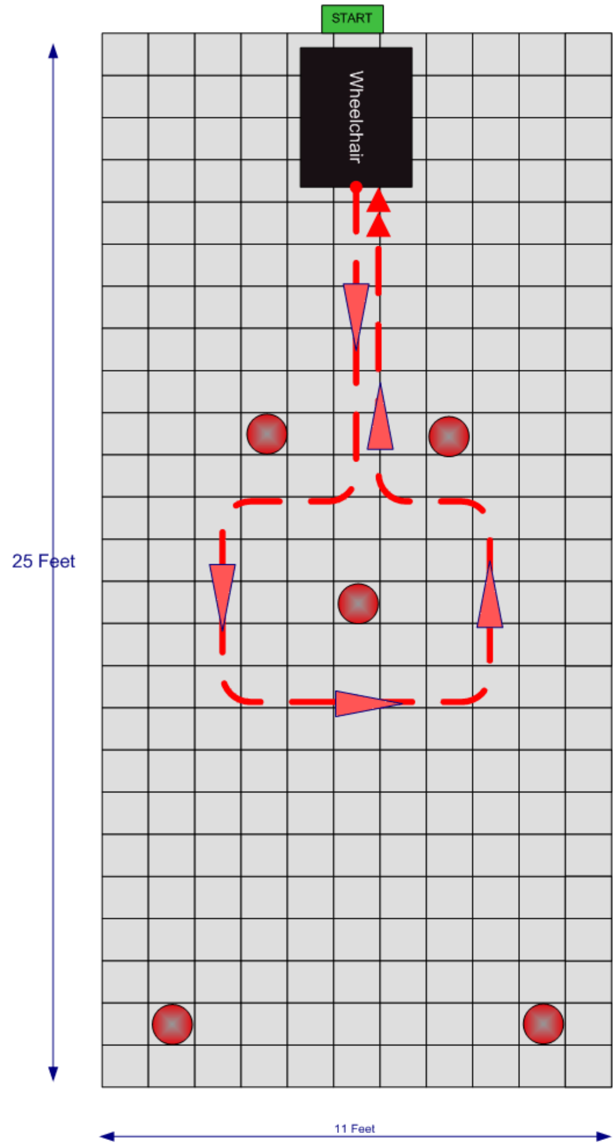
Visual feedback was provided by three LEDs (red, green, and yellow) in each sensor node. These LEDs were not powerful enough to see the status of the LEDs in a bright sunny day or in a room full of incandescent or fluorescent lighting. Future versions of the DSS should employ more powerful LEDs so the user can see the status in all lighting conditions.

APPENDIX A

OBSTACLE COURSES

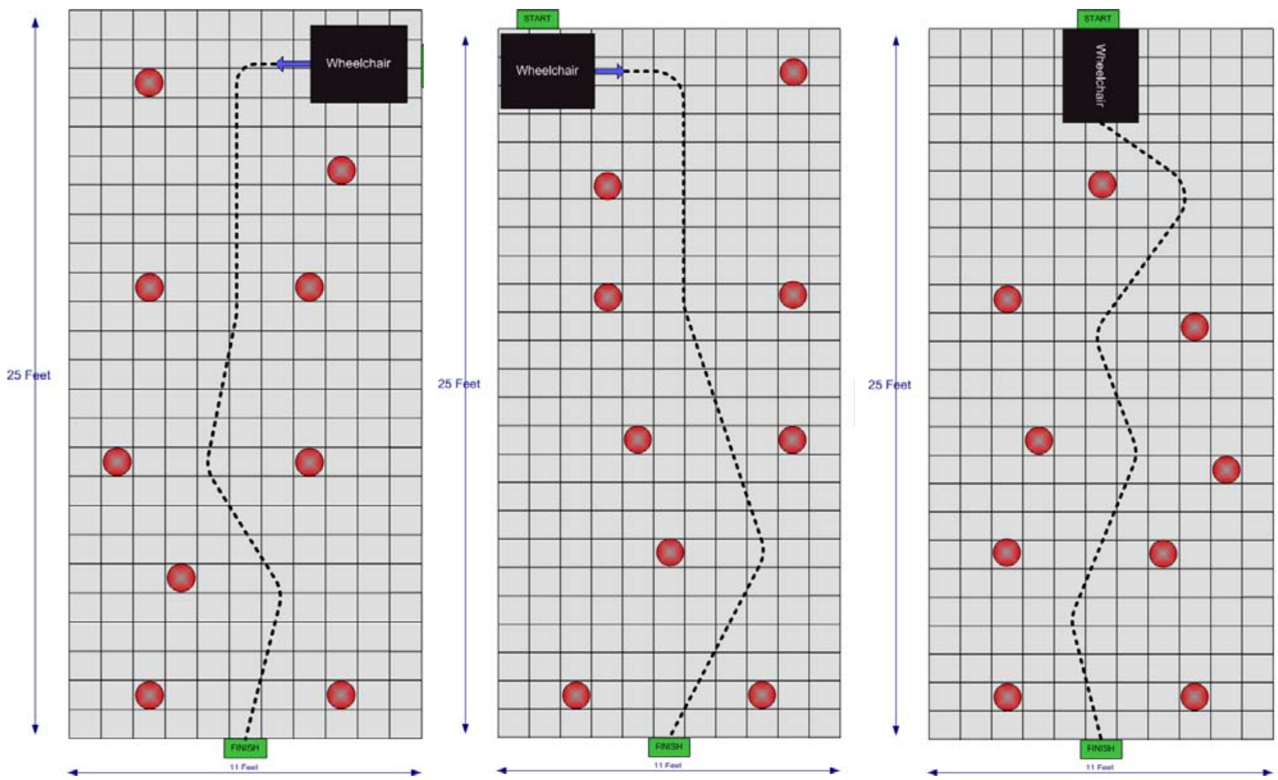
A.1 TRAINING OBSTACLE COURSES


START
Wheelchair
25 Feet
11 Feet

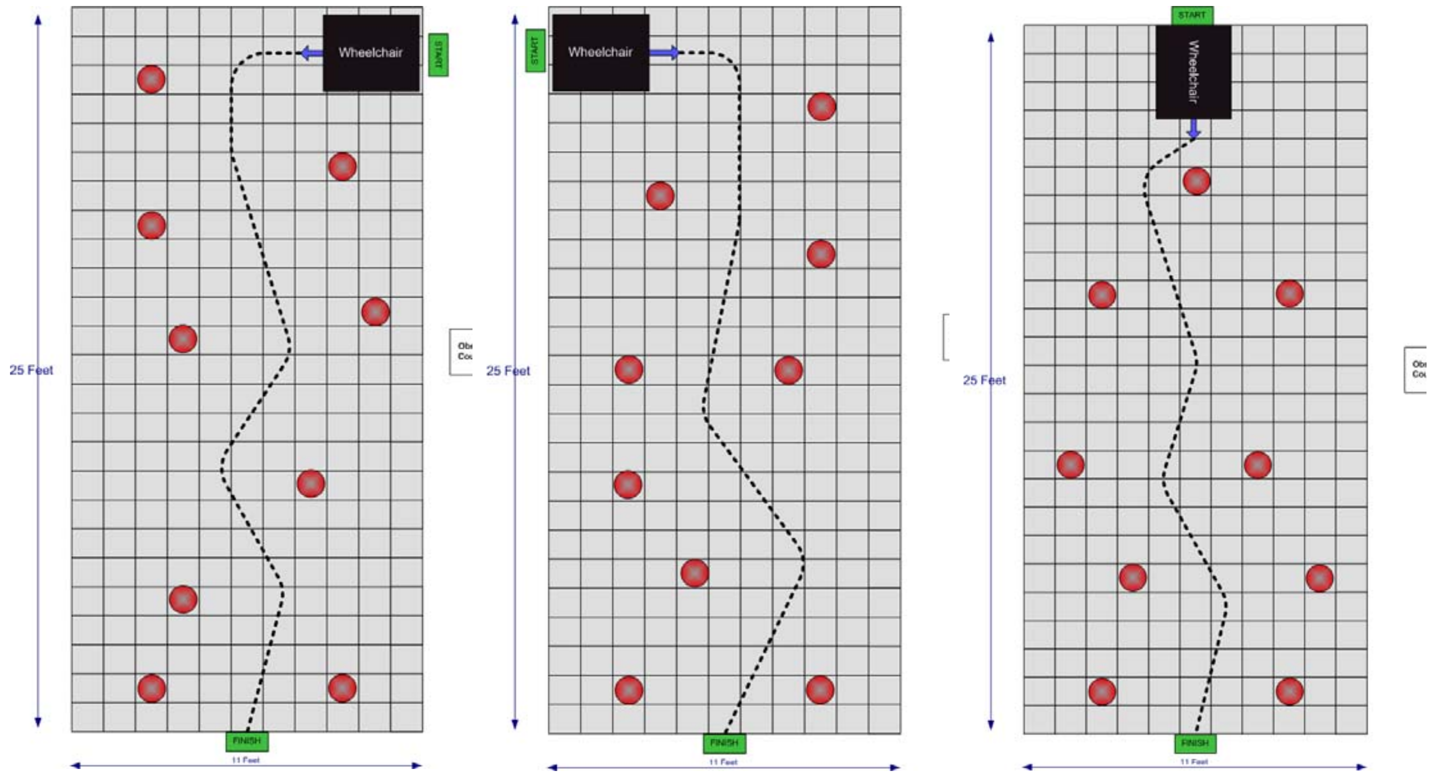

START
Wheelchair
25 Feet
11 Feet

A.2 FORWARD MOVEMENT OBSTACLE COURSES

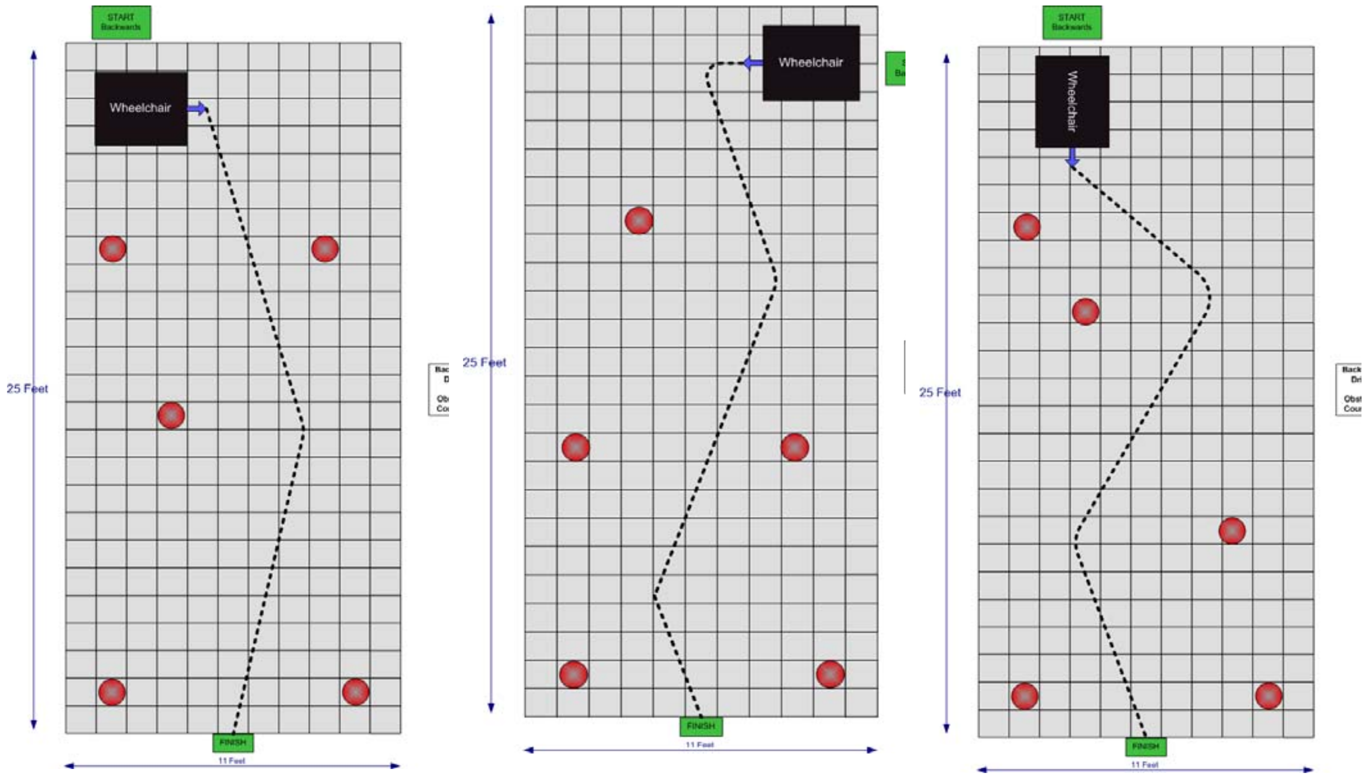
A.2.1 Obstacle courses set one

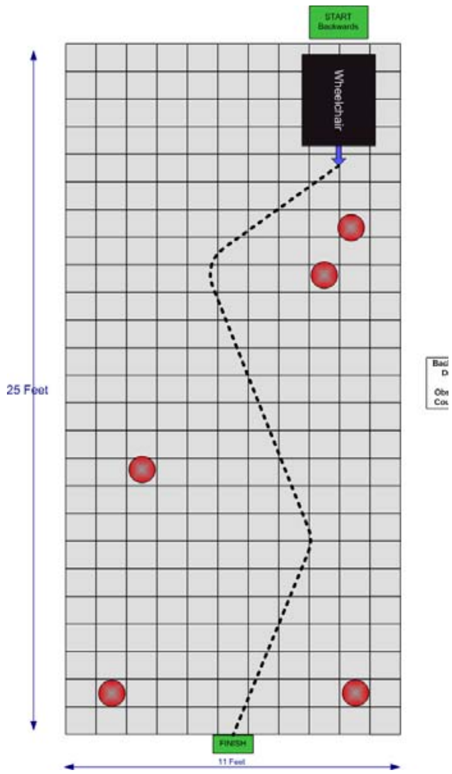


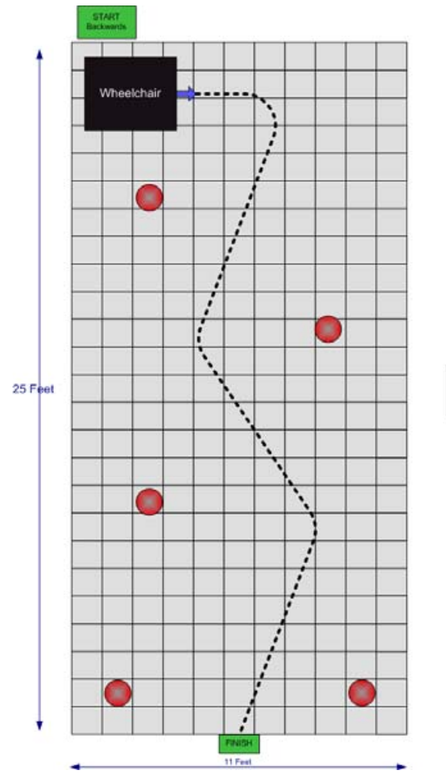
A.2.2 Obstacle Courses Set two

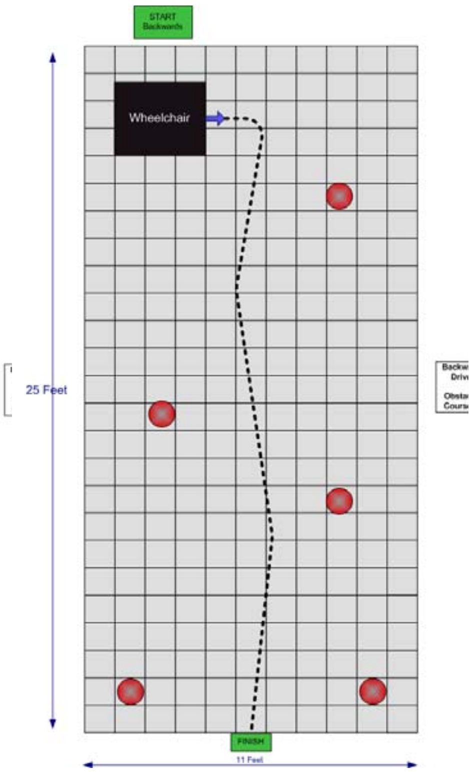


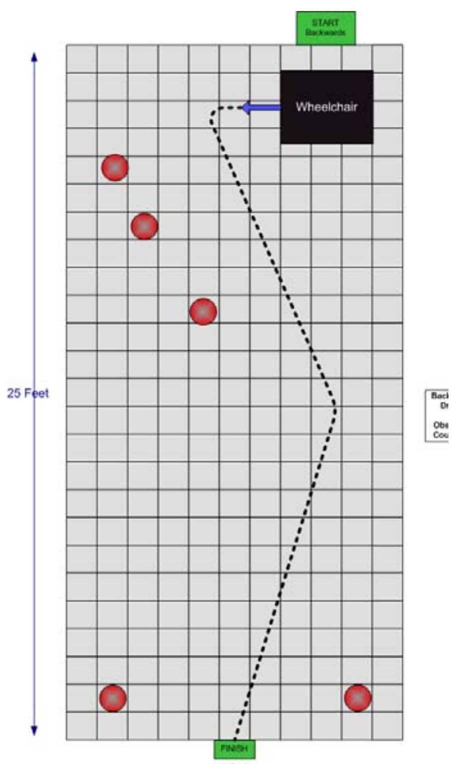
A.3 BACKWARD MOVEMENT OBSTACLE COURSES

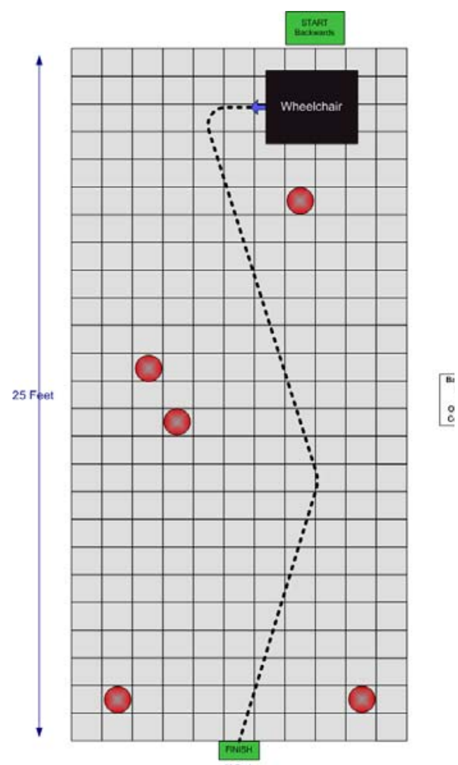


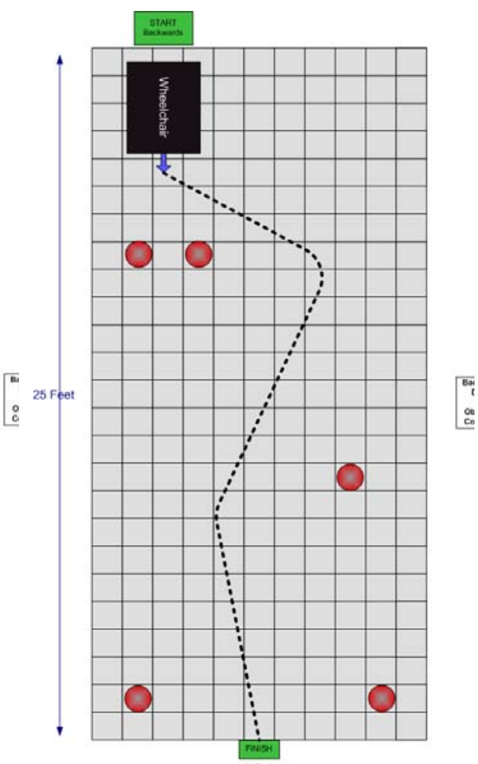

START
Backwards
Wheelchair
25 Feet
FINISH
11 Feet


START
Backwards
Wheelchair
25 Feet
FINISH
11 Feet


START
Backwards
Wheelchair
25 Feet
FINISH
11 Feet

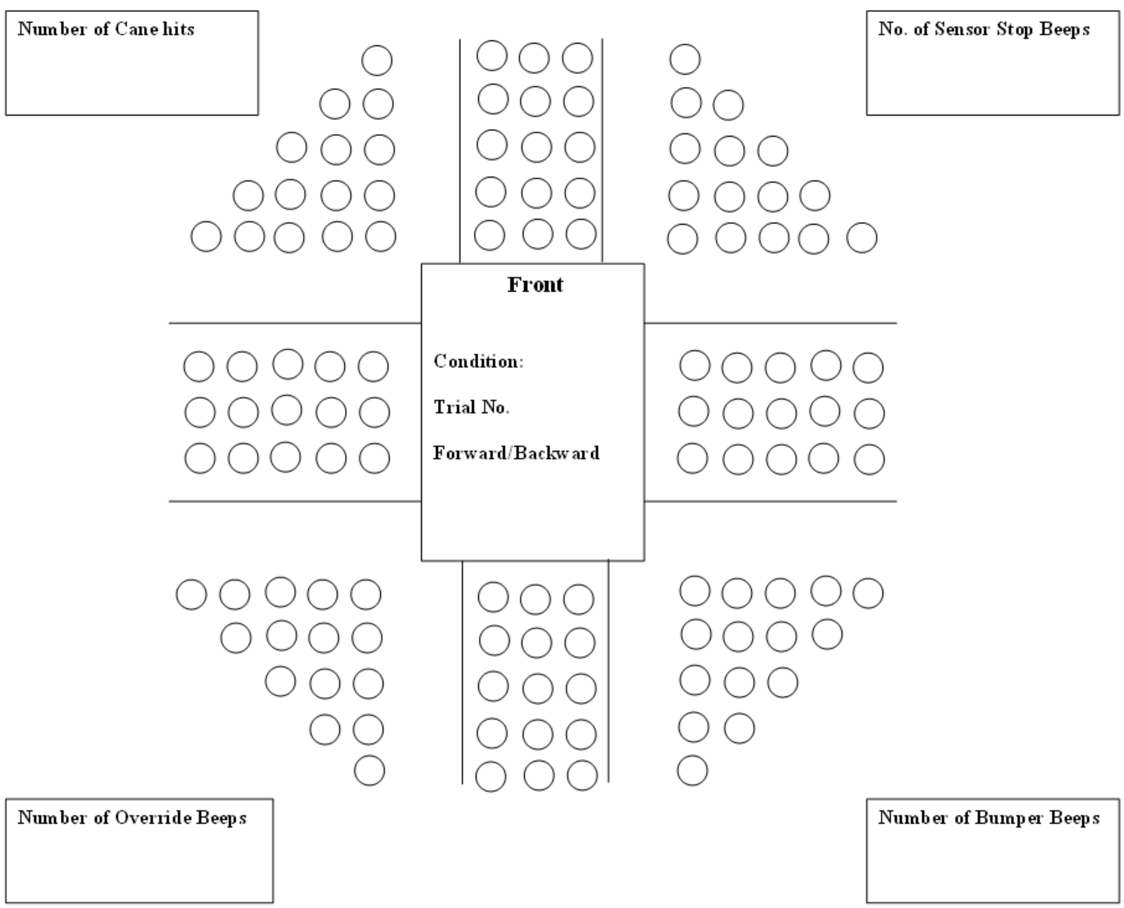

START
Backwards
Wheelchair
25 Feet
FINISH
11 Feet


START
Backwards
Wheelchair
25 Feet
FINISH
11 Feet


START
Backwards
Wheelchair
25 Feet
FINISH
11 Feet

APPENDIX B

DATA COLLECTION SHEET



APPENDIX C

NASA-TLX QUESTIONNAIRE

NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

APPENDIX D

MATCHING PERSON WITH TECHNOLOGY (MPT) QUESTIONNAIRE

Enter a [x] for the three items (A-L) that is most important to you. Then rate each device on the 12 items (A-L) according to the following scale and write your ratings (0 to 5) in the appropriate boxes.

5 = All the time (100% of the time)

4 = Often (Around 75% of the time)

3 = Half the time, neutral (About 50% of time)

2 = Sometimes (around 25% of the time)

1 = Not at all (0% of the time)

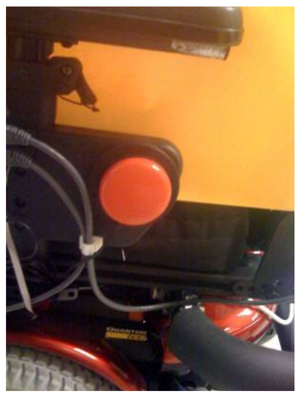
0 = Not applicable

	Question	<u>**Device:**</u> **Cane**	<u>**Device:**</u> **DSS**	<u>**Device:**</u> **DSS +Cane**
A	This device will help me in achieve my goals			
B	This device will benefit me and improve my quality of life			
C	I am confident I know how to use this device and its various features.			
D	I will feel more secure (safe, sure of myself) when using this device			
E	This device will fit well with my accustomed routine			
F	I have the capabilities and stamina to use this device without discomfort, stress and fatigue			
G	The support, assistance and accommodations exist for successful use of this device.			
H	This device will physically fit in all desired environments (living room, kitchen, bathroom, bedroom, etc.)			
I	I will feel comfortable (and not self conscious) using this device around family			
J	I will feel comfortable (and not self conscious) using this device around friends			
K	I will feel comfortable (and not self conscious) using this device at school or work			
L	I will feel comfortable (and not self conscious) using this device around community			
	Total (add A-L)			

Date:
User:

APPENDIX E

INSTRUMENTS USED IN THIS RESEARCH

 **Stop Switch**	 **Mode Switch**	 **Stop Watch**
 **Auditory Target**	 **Blind Folds**	 **Obstacle**

 **Sony Handycam**	 **White Cane**	 **Override Switch**

APPENDIX F

LIST OF SECTORS, ASSOCIATED SENSORS AND BUMPER SEGMENTS

Coverage	Node	Sonar	IR	Bumper
Sector 1	Sensor Node 1	UR1, UR2, UR3, UR4, UR5	IR1, IR2, IR3, IR4, IR5	Bumper1
	Sensor Node 2			
	Sensor Node 3			
	Sensor Node 4			
	Sensor Node 5	UR1, UR2, UR3, UR4, UR5	IR1, IR2, IR3, IR4, IR5	Bumper 9, Bumper 10
Sector 2	Sensor Node 1	UR1, UR2, UR3, UR4, UR5	IR1, IR2, IR3, IR4, IR5	Bumper1, Bumper 2
	Sensor Node 2			
	Sensor Node 3			
	Sensor Node 4			
	Sensor Node 5	UR1, UR2, UR3, UR4, UR5	IR1, IR2, IR3, IR4, IR5	Bumper 10
	Sensor Node 1	UR1, UR2, UR3, UR5	UR1,UR3,UR4, UR4	Bumper 1, Bumper 2

Sector 3	Sensor Node 2	UR3, UR4, UR5	IR4,IR5	
	Sensor Node 3			Bumper 3
	Sensor Node 4			
	Sensor Node 5	UR4	IR3, IR1, IR5	
Sector 4	Sensor Node 1	UR1, UR2, UR3, UR5	UR1,UR3,UR4, UR4	Bumper 2
	Sensor Node 2	UR3, UR4, UR5	IR4,IR5	
	Sensor Node 3			Bumper 3
	Sensor Node 4			
	Sensor Node 5	UR4	IR3, IR1, IR5	
Sector 5	Sensor Node 1	UR2, UR3	IR1, IR2, IR5	
	Sensor Node 2	UR3,UR4,UR5	IR3, IR4, IR5	
	Sensor Node 3	UR1,UR2	IR1	Bumper 3
	Sensor Node 4	UR1,UR2	IR1,IR2	
	Sensor Node 5			
Sector 6	Sensor Node 1	UR2, UR3	IR1, IR2, IR5	
	Sensor Node 2	UR3,UR4,UR5	IR3, IR4, IR5	
	Sensor Node 3	UR1,UR2	IR1	Bumper 3
	Sensor Node 4	UR1,UR2	IR1,IR2	
	Sensor Node 5			
Sector 7	Sensor Node 1			
	Sensor Node 2	UR1, UR2	IR1, IR2	Bumper 4
	Sensor Node 3	UR3, UR4, UR5	IR3, IR4, IR5	
	Sensor Node 4	UR3, UR4, UR5	IR3, IR4, IR5	

	Sensor Node 5			
Sector 8	Sensor Node 1			
	Sensor Node 2	UR1, UR2	IR1, IR2	Bumper 4, Bumper 5
	Sensor Node 3	UR3, UR4, UR5	IR3, IR4, IR5	
	Sensor Node 4	UR3, UR4, UR5	IR3, IR4, IR5	
	Sensor Node 5			
Sector 9	Sensor Node 1			
	Sensor Node 2	UR1, UR2	IR1,IR2	Bumper 4, Bumper 5
	Sensor Node 3	UR1, UR2, UR3, UR4, UR5	IR1, IR2, IR3, IR4, IR5	
	Sensor Node 4	UR1, UR2	IR1, IR2	Bumper 6
	Sensor Node 5			
Sector 10	Sensor Node 1			
	Sensor Node 2	UR1, UR2	IR1,IR2	Bumper 5
	Sensor Node 3	UR1, UR2, UR3, UR4, UR5	IR1, IR2, IR3, IR4, IR5	
	Sensor Node 4	UR1, UR2	IR1, IR2	Bumper 6, Bumper 7
	Sensor Node 5			
Sector 11	Sensor Node 1			
	Sensor Node 2	UR3, UR4, UR5	IR3, IR4, IR5	
	Sensor Node 3	UR1, UR2, UR3	IR1, IR2, IR3	
	Sensor Node 4	UR1, UR2	UR1, UR2	Bumper 6, Bumper 7
	Sensor Node 5			
	Sensor Node 1			
	Sensor Node 2	UR3, UR4, UR5	IR3, IR4, IR5	

Sector 12	Sensor Node 3	UR1, UR2, UR3	IR1, IR2, IR3	
	Sensor Node 4	UR1, UR2	UR1, UR2	Bumper 7
	Sensor Node 5			
Sector 13	Sensor Node 1			
	Sensor Node 2	UR1, UR2	IR1, IR2	
	Sensor Node 3	UR4,UR5	IR5	Bumper 8
	Sensor Node 4	UR3,UR4,UR5	IR3,IR4, IR5	Bumper 7
	Sensor Node 5	UR2, UR3	IR1, IR2, IR5	
Sector 14	Sensor Node 1			
	Sensor Node 2	UR1, UR2	IR1, IR2	
	Sensor Node 3	UR4,UR5	IR5	Bumper 8
	Sensor Node 4	UR3,UR4,UR5	IR3,IR4, IR5	
	Sensor Node 5	UR2, UR3	IR1, IR2, IR5	
Sector 15	Sensor Node 1	UR4	IR1	
	Sensor Node 2			
	Sensor Node 3			Bumper 8
	Sensor Node 4	UR3, UR4, UR5	IR3, IR4, IR5	
	Sensor Node 5	UR1, UR2, UR3, UR4,UR5	IR1, IR2, IR3, IR4, IR5	Bumper 9
Sector 16	Sensor Node 1	UR4	IR1	Bumper 1
	Sensor Node 4	UR3, UR4, UR5	IR3, IR4, IR5	
	Sensor Node 5	UR1, UR2, UR3, UR4,UR5	IR1, IR2, IR3, IR4, IR5	Bumper 9, Bumper 10

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