An Intelligent Powered Wheelchair for Users with Dementia: Case Studies with NOAH (Navigation and Obstacle Avoidance Help)

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Abstract

Intelligent wheelchairs can help increase independent mobility for elderly residents with cognitive impairment, who are currently excluded from the use of powered wheelchairs. This paper presents three case studies, demonstrating the efficacy of the NOAH (Navigation and Obstacle Avoidance Help) system. The findings reported can be used to refine our understanding of user needs and help identify methods to improve the quality of life of the intended users.

Introduction

Older adults in long-term care (LTC) facilities who are unable to walk or propel themselves in manual wheelchairs are usually prescribed powered wheelchairs for increased mobility. However, cognitively-impaired drivers are often unable to operate these wheelchairs safely and are thus excluded from powered wheelchair use. A significant proportion of LTC residents (60-80%) have dementia (Marcantonio 2000). The inability of these elderly residents to navigate independently often leads to an increased reliance on caregivers to meet the residents' mobility needs.

In order to address the above issues, we have developed an intelligent wheelchair system called NOAH (Navigation and Obstacle Avoidance Help) (Viswanathan et. al 2000). Most existing intelligent wheelchairs (Simpson 2005) are autonomous, thus preventing or minimizing user control. Alternatively, other wheelchairs that only assist in collision avoidance and require users to plan their own routes (How, Wang, and Mihailidis 2011) are not appropriate for our intended users, who are often unable to determine their location and/or desired destination. The objective of our system is to maximize user independence and mobility while minimizing safety risks. The system has two main functionalities: 1) preventing collisions, and 2) providing wayfinding assistance. We use a stereo-vision camera for obstacle detection and wheelchair localization due to its relatively low cost and power requirements, as well as its ability to perform in natural settings. The collision avoidance module prevents wheelchair motion towards nearby obstacles. The wayfinding module uses a probabilistic model (a Partially Observable Markov Decision Process) to first estimate the user's independence and responsiveness levels, and subsequently determine the optimal system action (do nothing, issue direction prompt or issue task reminder). We use audio prompts (e.g. "Turn slightly to the left", "Off-route! Turn right") to allow users with visual impairment to benefit from the wayfinding assistance provided, and to minimize potential distractions caused by the use of visual prompts. Further details on the system design can be found in (Viswanathan et. al 2000).

In this paper, we describe an efficacy study conducted with real users. While we have previously presented raw quantitative and qualitative data for all six participants in (Viswanathan et. al 2000), in this paper we present three detailed case studies. We perform statistical analyses for these three participants and report on further details regarding user interactions with the system, prompting accuracy and compliance.

Efficacy Study Design

In order to evaluate the system with the target user population, we conducted an efficacy study, obtaining quantitative and qualitative data. Out of the six participants who completed the study, we profile here three participants who benefited from the system in different ways. Details on the study methodology and data for other participants can be found in (Viswanathan et. al 2000). The study protocol is summarized below.

Recruitment

The study was conducted at a long-term care facility in Toronto, Ontario, Canada. Participants with a mild-to-moderate cognitive impairment (as determined by standard cognitive assessments) were included. Priority was given to participants who, in addition to meeting the inclusion criteria, experienced feelings of disorientation and/or had visual impairments. Participants were excluded if they had a reported history of aggression. In addition, participants with significant prior experience with a powered wheelchair were excluded in order to control for potential experience-dependent effects.

Study Methodology

The single subject research design (SSRD) is typically used to study the behavioral change an individual demonstrates as a result of some treatment (Ottenbacher 1986). Each participant is exposed to a baseline and an intervention phase. Performance is measured through repeated observations of user behavior during each phase, allowing the researcher to identify performance patterns within phases, and to compare these patterns across phases.

The efficacy study consisted of baseline and intervention phases, A (where NOAH was de-activated) and B (where NOAH was activated), respectively. Each participant completed both phases. A counterbalanced study design was chosen where half of the participants were randomly chosen for A-B phase ordering. The remaining half were assigned B-A ordering. A training session was conducted prior to each phase, followed by eight test sessions (runs). A total of sixteen runs were completed by each participant.

Apparatus and Set-up

The study was conducted in a 50 m X 50 m room in the basement of the LTC facility. A maze was constructed in this room out of Styrofoam boards, with a stop sign taped on a board at the end of the maze. A maximum wheelchair speed of 0.25 m/s was chosen in order to ensure driver safety. In addition, two different and alternating obstacle layouts were used in order to control for learning effects. A 2-D representation of the maze was constructed by a manually-driven Pioneer 3-AT robot running mapping software (http://www.ros.org/wiki/gmapping). The final map (with a resolution of 0.05 m) was an image file in portable graymap (PGM) format. The wheelchair localized itself with respect to this map during the test runs.

Procedure

At the beginning of each phase, a training session was conducted for every participant in an open area, to allow him/her to learn how to operate the wheelchair (with or without NOAH). At the end of the training session, participants were escorted in their manual wheelchair along the optimal route to the specified goal (the stop sign) at the end of the maze. They were informed that they had to follow this route during subsequent runs.

At the beginning of each run, participants were asked to report on their confidence in navigating along the specified route using learning transference acquired from the training session and/or previous runs. Participants were then asked to navigate to the stop sign by following the pre-specified route. At the end of each run, participants completed a survey regarding wheelchair usability. At the end of each phase, participants were asked questions regarding their level of satisfaction, as well as open-ended questions regarding the device.

Data Analysis

Visual analysis is often the primary method of analysis for SSRDs. We analyzed frontal collisions and route lengths visually through comparison of the sample mean (μ), standard deviation (σ), and trend. The C-statistic (Tryon 1982) is used to determine effectiveness of the treatment by determining whether there is a trend in sequential evaluation measures in terms of slope and magnitude of change. This method was chosen since it only requires a minimum of eight data points per phase, can be used with serially dependent data, and is relatively easy to compute. The baseline data is first analyzed with the C-statistic to detect a significant trend ($p<0.05$). If a significant trend does not exist, the baseline data is combined with the intervention data, and the C-statistic is re-computed for the combined data. A statistically significant C-statistic value for the entire series might provide evidence for a shift in level and/or trend, however it cannot conclude that the change was caused by the intervention. The C-statistic is thus used to supplement visual analysis of the data.

Prompting accuracy and user responses to system prompts are also reported. *Compliance* refers to user actions that agree with the system prompt, while *Non-compliance* refers to user actions that disagree with the prompt. *No response* is used to refer to situations where the user does not perform any action upon receiving a prompt.

Case Studies

Participant 1

Participant 1 was 97 years old and had a moderate cognitive impairment. She had a severe visual impairment, but was able to propel herself in her manual wheelchair. In addition, she could not understand some of the audio prompts during the training session, so the recordings were slightly simplified and modified to include words translated to her native language.

Fig. 1 shows the frontal collisions for participant 1. Visually, there is a large discontinuity in performance between the last baseline run and the start of the intervention phase, which is a criterion for acknowledging that a mean change occurred because of the intervention (Ottenbacher 1986). The mean number of collisions is lower with the intervention. Specifically, the minimum number of collisions in the baseline phase is greater than

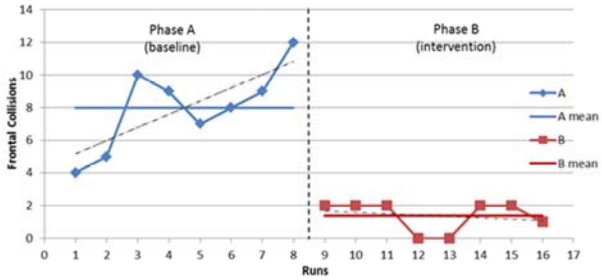


Figure 1: Frontal collisions for participant 1.

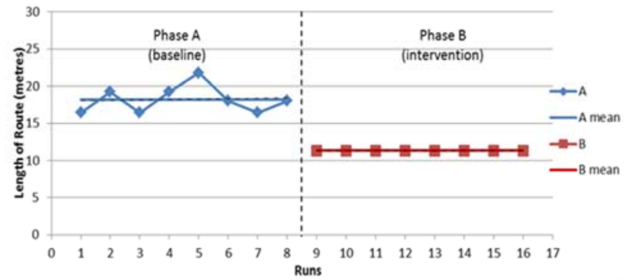


Figure 2: Route lengths for participant 1

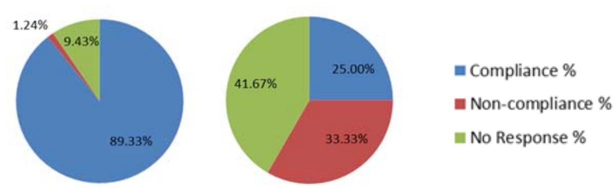
the maximum number of collisions in the intervention phase. The variance in the number of collisions also appears to be lower in the intervention phase. The C-statistic reveals that although no significant trend is found in the baseline data (Z=1.41), a significant trend is found when the intervention data is appended to baseline data (Z=2.53, p<0.01). Thus, the magnitude of change when the intervention is introduced is unlikely to have occurred by chance.

The results suggest that system increased safety for participant 1. Due to severe visual impairments, participant 1 could not see obstacles in front of the wheelchair and often drove through them when NOAH was not activated. The stopping mechanism decreased her frontal collisions. However, we found she was often unable to detect free space herself (due to her poor vision), and thus might have benefited from additional audio prompts that provided free space information. Participant 1 was also generally confused about joystick operation at times or did not push the joystick hard enough to initiate wheelchair motion. In these cases, the researcher asked the participant which direction she wanted to move in and assisted her in operating the joystick (by telling her to push harder or pushing her hand on the joystick towards her desired direction for a few seconds). This suggests that further training or an alternate feedback mechanism (in addition to just audio prompts) might be required by some users. Additionally, the usability of the joystick interface on the wheelchair could be improved or other interfaces could be explored. Also, although NOAH was able to reduce the number of frontal collisions, it did not completely eliminate them due to the presence or appearance of obstacles in the camera's blind spots.

Fig. 2 shows the length of the route taken by participant 1. There is a large discontinuity in performance between the last baseline run and the start of the intervention phase. The mean of the route length is lower with the intervention. The minimal route length in the baseline phase is much greater than the maximum route length in the intervention phase. The variance in the distance travelled also appears to be lower in the intervention phase. From inspection, it appears that the intervention (NOAH) has an impact on the distance travelled for participant 1. A statistically significant change is found with the C-statistic (Z=2.93, p<0.01).

Without the system, the participant was found to wander in the maze since she could not remember the specified route due to memory impairment (she also needed to be reminded of the task before every run), often revisiting previous locations. However, when the system was in use, participant 1 was found to be very responsive to prompts, often responding to instructions by echoing or saying "yeah". During one occasion, the system issued an incorrect prompt due to a localization error (the wheelchair was estimated to be closer to a turn than it really was). It prompted her to turn left into an obstacle outside the camera's view. The participant responded by saying "No sense!" and correctly ignored the prompt. This interaction suggests that the participant saw the system as a collaborator that helped her but was also likely to make mistakes, and was thus able to engage in a shared decision-making process. The participant was also found to laugh and respond positively to prompts that contained her native language, suggesting that language can help to improve usability of the system.

The overall prompting accuracy in trials with participant 1 was 89.36%, while the mean accuracy over the 8 intervention trials was 88.98%. The minimum and maximum accuracy seen in the intervention trials were 70.15% and 100% respectively.



Correct Prompts Incorrect Prompts

Figure 3: Prompt responses by participant 1

Responses to all correct and incorrect prompts by participant 1 are shown in Fig. 3. While compliance with correct prompts is quite high, compliance with incorrect prompts is lower. Analysis of the video data reveals that participant 1 ignored or failed to respond to incorrect prompts that suggested motion in the direction of obstacles (hidden from the camera's view). In contrast, she tended to comply with incorrect prompts when she did not see obstacles blocking her path. In one run, she wanted to move forward as some correct prompts were suggesting, however she expressed anxiety because she saw a painted black line on the floor in front of her that she thought was a crack she might fall into (she pointed to the line and gestured the action of falling down). This led to the acts of *No Response* observed in Fig. 3. She only moved forward when she saw the researcher walk across the painted line to demonstrate that the floor was even.

Results also indicate that completion times tended to be lower in the intervention phase. This was mainly due to the fact that the participant was taking the shortest route to the destination when the system was in use, rather than wandering. In addition, by encouraging the participant to stay away from obstacles, the system was able to help the participant to navigate in open spaces, thus saving time spent maneuvering out of major collisions (which the participant found difficult to do).

The participant's perceived performance (as determined by the survey) was much better with the system. She also provided lower ratings for effort and frustration in the intervention phase. It is interesting to note that when the system was in use, the participant repeatedly said "more!" at the end of the trial, indicating through gestures that she wanted more driving time. In contrast, the participant said "enough!" as she neared the destination when the system was not in use. Thus, the system possibly lowered her fatigue (effort) and increased motivation by increasing safety and decreasing driving times. The participant was found to be less anxious regarding collisions with the intervention, but this observation could be attributed to increased user familiarity with the task.

Participant 5

Participant 5 was 91 years old and had a mild cognitive impairment. She used a walker and was highly mobile, but tended to wander because of the memory deficits and high disorientation found in her cognitive assessment. Participant 5 had A-B phase ordering.

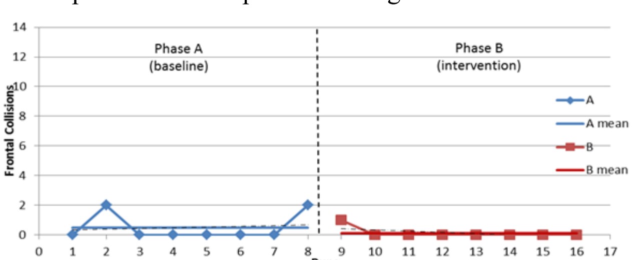


Figure 4: Frontal collisions for participant 5

Fig. 4 shows the frontal collisions for participant 5. There appears to be a slight discontinuity between phases, however the mean frontal collision and variance is only slightly lower with the intervention. In addition, the total magnitude of collisions in both phases is quite low, however the system maintains a lower overall number of frontal collisions. No statistically significant change is found with the C-statistic (Z=0.22). Note that the missed detection in the intervention phase (run 9) occurred when the participant covered a lens with her hand.

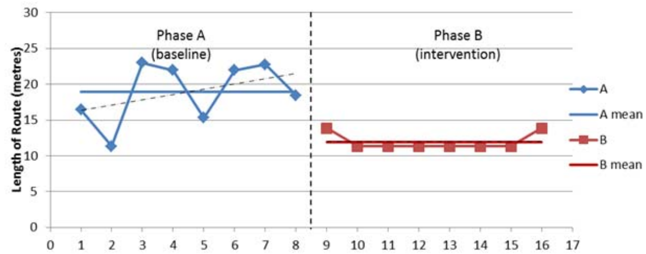


Figure 5: Route lengths for participant 5.

Fig. 5 shows the length of the route taken by participant 5. There is a discontinuity in performance between phases. The mean route length and variance is lower with the intervention. From inspection, it appears that the intervention (NOAH) has an impact on the distance travelled for participant 5. A statistically significant change is found with the C-statistic (Z=2.02, $p<0.05$).

Without the system, the participant wandered and revisited previous locations in the maze since she could not remember the specified route due to memory impairment. When the system was in use, participant 5 was found to be very responsive to prompts and would often respond to instructions by clarifying (e.g. "left?") or saying "yeah". When she did not hear prompts in the baseline phase, she would often ask the question "where am I going?", thus suggesting that the system decreased her confusion. During two intervention runs, prompting errors resulted in detours that were corrected by subsequent prompts.

Surveys indicated that during the baseline phase, participant 5 thought of the runs as simply driving tasks. However, she viewed the runs in the intervention phase as tasks that involved getting to a specific location within a specific time. She recognized that she was being guided to a destination.

The overall system accuracy in trials with participant 5 was 84.46%, while the mean accuracy over 8 intervention trials was 85.12%. The minimum and maximum accuracy seen in the intervention trials were 66.67% and 97.06% respectively.

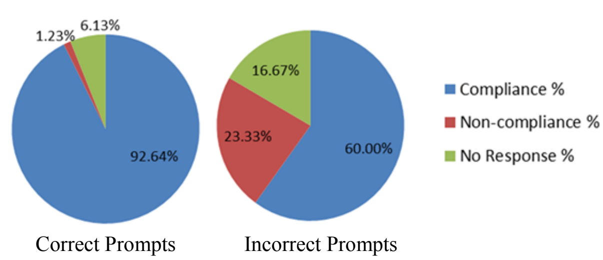


Figure 6: Prompt responses by participant 5

Responses to all correct and incorrect prompts by participant 5 are shown in Fig. 6. Compliance with correct prompts is quite high, while compliance with incorrect prompts is lower. However, participant 5 complied with incorrect prompts more often than she disobeyed or ignored them. Similar to participant 1, participant 5 did not comply with or respond to incorrect prompts that suggested motion in the direction of obstacles (hidden from the camera's view) or dead-ends. She complied with incorrect prompts at junction points, resulting in detours during the first and last intervention runs (leading to longer route lengths) that were corrected by subsequent correct system prompts. Since most incorrect prompts issued to participant 5 were at junctions, her overall compliance with incorrect prompts was found to be very high.

Participant 6

Participant 6 was 80 years old and had a mild cognitive impairment. She used a walker regularly and was able to navigate around the facility independently. She had left-right confusion, and was thus provided with markers on her hands to help her in identifying directions. She had B-A phase ordering.

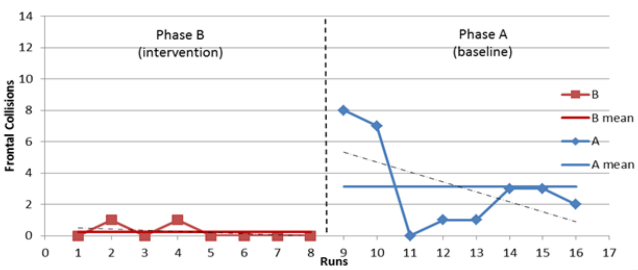


Figure 7: Frontal collisions for participant 6

Fig. 7 shows the frontal collisions for participant 6. Visually, there is a large discontinuity in performance between phases. The mean number of collisions is lower with the intervention. The variance in the number of collisions also appears to be lower in the intervention phase. There also appears to be a decreasing trend during the baseline phase, suggesting that the participant might be improving her collision avoidance performance over time. From visual inspection it appears that the intervention (NOAH) reduces the mean number of frontal collisions for participant 6. However, no statistically significant change is found with the C-statistic (Z=1.27), possibly due to the large trend seen within the baseline phase.

The results suggest that system increased safety for participant 6. The high number of collisions at the start of the baseline phase also suggests that the system might be creating user dependence on automated collision avoidance. Over time, the participant learnt how to avoid collisions in the baseline phase by focusing more on the task, and stated that she had to "think a lot" while driving around them. The data also suggest that NOAH might not be useful as a training tool for powered wheelchair use, since users do not actually learn how to avoid obstacles while using the system. The participant mentioned that she would want to use the anti-collision system since she thought driving in the facility would be dangerous otherwise.

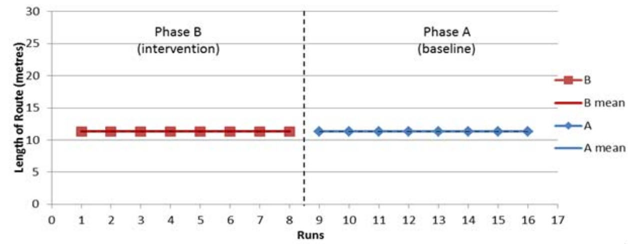


Figure 8: Route lengths for participant 6.

Fig. 8 shows the length of the route taken by participant 6. No visual discontinuity is found between the phases. The mean and variance are the same in both phases. Thus, the wayfinding module did not appear to help participant 6, possibly because her baseline wayfinding performance was quite high (she was confident that she remembered the route before every run).

The overall system accuracy in trials with participant 6 was 78.71%, while the mean accuracy over 8 intervention trials was 84.72%. The minimum and maximum accuracy seen in the intervention trials were 53.66% and 100% respectively.

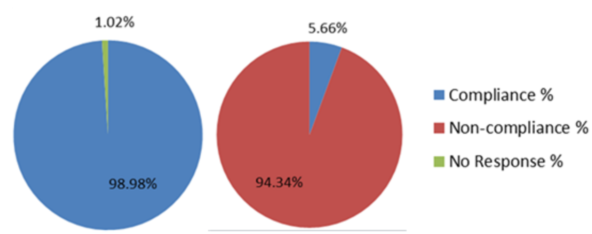


Figure 9: Prompt responses by participant 6

Responses to all correct and incorrect prompts by participant 6 are shown in Fig. 9. While compliance with correct prompts was quite high, almost all incorrect prompts were correctly ignored. This (correct) non-compliance with incorrect prompts is quite different from the results seen with the previous two participants. Participant 6 had a high baseline wayfinding performance, and might not have needed assistance, thus correctly ignoring incorrect prompts even at junction points.

Key Findings

Although mean collisions are lowered for all participants, we notice large differences between participants in terms of their collision avoidance ability. Results for participant 1 suggest that the collision avoidance module is particularly useful to cognitively-impaired users with vision impairment, and can help improve safety for these users. In addition, visually-impaired users could benefit from additional verbal prompts indicating free space.

Participants 1 and 5 benefited most from the wayfinding module. These participants did not usually remember the task (finding the stop sign), and when they were reminded, did not know the location of the stop sign. Participant 6 reported high confidence regarding the route and did not benefit from the wayfinding module, but did benefit from the collision avoidance module.

Although compliance with correct prompts was high across all users, we noticed a distinct difference in the rates of compliance with incorrect prompts. While users who were confident about the route showed low compliance with incorrect prompts, participants who had poor baseline wayfinding performance and were less confident in their self-reports complied more often with incorrect prompts, specifically at decision points. These results imply that participants with lower self-ratings of confidence rely more highly on the prompts for assistance, and are able to improve their wayfinding performance by following correct prompts. However, these participants are also more likely to comply with incorrect prompts, thus highlighting the need for a high level of system accuracy, specifically at decision points, to ensure effective navigation and to minimize wandering. A large number of incorrect prompts could also lead to confusion and frustration among users, who might choose to ignore all prompts (including correct ones) as a result.

Prompting errors occurred mainly because of localization errors caused by occluded visual landmarks in the cluttered maze. In at most two intervention runs per participant, these errors were corrected by manual re-starts of the localization module at a pre-specified location (roughly mid-way along the route). Other errors occurred due to accumulated localization error towards the end of the route, and delayed prompting. Mechanical odometry measurements obtained through wheel encoders, and/or the use of pre-registered visual landmarks can be used to improve localization accuracy in the future.

The absence of safety hazards in the test environment possibly reduced anxiety and fear of collisions, making participants more likely to drive through the foam obstacles. Future studies should test the system in more realistic environments. Performance expectancy and the presence of the researcher might have also affected user performance and ratings. In addition, the route lengths reported are specific to the maze constructed for this study in a limited amount of space. In a more realistic environment, a single deviation from the optimal route could lead to arbitrarily longer routes, depending on the floor layout. Thus, the benefits provided by the wayfinding system (through increased timeliness, and in turn, decreased user fatigue) are likely to be underestimated in this study. Finally, the small sample size presents challenges in generalizing the study results to the larger population of older adults with cognitive impairment. The large amount of variation in functional abilities observed even in the limited number of test users suggests that the system needs further testing and validation to identify areas for improvement.

The above case studies provide key insights on the possible benefits of intelligent wheelchairs to older adults with cognitive impairments. Our results demonstrate the high diversity of the target population, and highlight the need for adaptive assistive technologies that account for varying user capabilities and requirements. By improving the users' collision avoidance and wayfinding performance, the system has shown promise in increasing independent mobility for a population that is currently denied powered wheelchairs due to safety concerns. Improvements in localization accuracy and computational speed will help improve user performance and satisfaction. We hope that further user studies will help characterize user needs and allow us to improve the quality of life of elderly residents.

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