Analyzing Drivers' Affect for the Design of Intelligent Wheelchairs for Older Adults with Cognitive Impairment

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ABSTRACT
Potential powered wheelchair users may be denied access out of safety concerns due to cognitive, physical or perceptual impairments. To restore independent mobility, wheelchairs that provide driving assistance are under development. To establish requirements for these smart wheelchairs, 10 older adults with mobility and cognitive impairments were asked to drive in five scenarios, with a mock intelligent wheelchair operated by a tele-operator providing three different types of assistance, ranging from simple collision avoidance to fully autonomous driving. Videos of the trials were coded to extract participants' affect during the tasks in relation with usability issues identified during the analysis of the interviews and questionnaire results. Affect with regards to two key usability issues was considered: (1) discomfort as an indicator of safety concerns and (2) conflict as an indicator of mismatched user expectations and system behavior. Instances of conflict were inversely associated with the level of tele-operator intervention. Discomfort levels were generally low with the exception of one scenario/control mode combination where fear of injury was noted.

CCS Concepts
• Human-centered computing~Accessibility technologies • *Human-centered computing~Empirical studies in HCI* • **Social and professional topics~People with disabilities**

Keywords
Intelligent wheelchairs; human-robot interaction; affect; discomfort; conflict.

1. INTRODUCTION
Powered wheelchairs (PWC) can be prescribed to individuals who are mobility impaired and are unable to self-propel using manual wheelchairs. Access to powered mobility can be denied by therapists due to cognitive, sensory or physical impairments that may hinder one's ability to drive safely [9]. The resulting loss of independent mobility can lead to reduced social interactions and ability to perform activities of daily living [10]. Intelligent powered wheelchairs are PWCs with added functionalities that can assist with driving and navigation, and are a promising solution to restore independent mobility in those currently denied access to PWCs [25, 34]. A comprehensive review of the research on this technology can be in found in [27]. Few of these groups engage potential users in the design or validation process.

Two million older adults in the US use wheelchairs [2] and 1 in 9 has dementia [1]. In this population, cognitive status is the main factor in the prescription of manual versus powered wheelchairs [17]. Users' sensory, motor and cognitive abilities and how these can evolve over time must be considered [22]. There is limited literature regarding the design of intelligent PWCs for older adults with cognitive impairment [30]. In this study, older adults with cognitive impairment performed driving tasks using a mock intelligent wheelchair to gain a better understanding of this population's needs and abilities with regards to PWCs. While [24, 29] reported on user attitudes and perceptions by analyzing data obtained through user interviews before and after trials, this paper focuses on the real-time affective experience of the participants and the implications for future designs. Analyzing users' affect to describe the user experience in a Human-Computer Interaction complements usability studies [8]. Usability issues identified in [29] served as a starting point to identify expressions of affect indicative of discomfort or conflict with the system. This quantitative analysis based on coded gestures and instances of speech aims to validate findings in [29] and allow for comparison of control modes and driving scenarios. This methodology follows the transition from a qualitative content analysis to a summative analysis to identify patterns and interpret results [14].

2. METHODS
2.1 Study Overview
Following ethics approval from the research team members' host institutions and all test sites, recruitment for the study took place at three long-term care facilities in Vancouver, Canada. A purposive sampling method was used. Designated facility staff identified residents based on the following inclusion criteria: 1) be over the age of 50; 2) have mild-to-moderate cognitive impairment as determined by clinical assessments such as the

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Mini Mental State Examination [11]; 3) be able to sit in a PWC for an hour per day; 4) be able to operate a joystick; 5) have basic communication skills in English; and 6) have difficulties walking or self-propelling a manual wheelchair. Ten participants (6 females, 4 males) of age 62 to 98 years completed the protocol.

A commercial PWC was modified by AT Sciences, LLC and the research team to allow operation through the wheelchair joystick and tele-operation to simulate shared or autonomous control strategies. The tele-operator could intervene to override the heading or the speed of the wheelchair through a PlayStation® 3 interface. Audio and haptic feedback were provided to the user to indicate chair behaviors e.g. "slowing down". Following training, participants were asked to drive the wheelchair in five scenarios chosen from the Power-mobility Indoor Driving Assessment [5] :

1. Table docking: driving up to and under a table.
2. Back-in parking: driving backwards and parking between two chairs.
3. Hallway: driving down an L-shaped hallway and back.
4. Maneuverability: driving around a short obstacle course.
5. Elevator: driving into and out of an elevator.

In each scenario, participants drove under three control modes:

1. Basic safety (BS): The tele-operator could restrict the wheelchair's speed. This allowed the tele-operator to slow down the wheelchair when the user was getting too close to the obstacle (less than 0.6 m or 2 feet away). If the user continued in the same direction, the tele-operator would stop the chair at a distance of 0.3 m or 1 foot.
2. Steering correction (SC): The tele-operator could control both direction and speed. This allowed him to redirect the user towards free space when he drove too close to an obstacle. The tele-operator would relinquish control to the user once the threat of collision was overcome.
3. Autonomous driving (AD): The tele-operator drove the wheelchair for the full duration of the task without any input from the user. The user could request a full stop by pulling back on the joystick or saying "stop".

More details on the system and the study are in [21, 29, 32]. During the trials, one researcher tele-operated the PWC and one researcher supervised the session and interviewed participants following the completion of the trials for each mode. A third researcher filmed the sessions. Participants were also interviewed before and after completing all scenarios. Results from the pre- and post- driving trials interviews are reported in [24] and the results from driving interviews are in [29]. This paper analyzes video data to study participants' affect during the driving trials.

2.2 Affect Analysis

Negative behaviors during interactions with the system were chosen to further understand the user experience, considering a social desirability response bias and a potential unwillingness to give ratings of "not satisfied" in standardized questionnaires were reported in similar studies [31, 36]. In studies where participants have limited short-term memory, the ability to comment on their driving experiences after the trials may limit response validity and could be improved with the use of observational data or open-ended questions to corroborate results [13]. Affect analysis is a good alternative to unveil their impressions of the system since the expression of affect is still present even when memory is affected [19]. The circumplex model of affect is a popular tool in psychology to describe emotions based on two axes: pleasure-displeasure and degree of activation [26]. This model can be used to characterize an individual's emotional state in social and non-verbal interactions. Grouping related behaviors is recommended to gain richer insights into individuals' experience since emotion is conveyed and understood through a constellation of cues [3]. In this study, the groups of related behaviors were labeled as either discomfort or conflict and were identified based on two main usability issues verbalized by study participants [29]. The use of bodily expressions to analyze affect is not as widespread as using facial expressions, but can be as reliable [7]. For instance, recognition accuracy for fear and anger was not significantly different using either type of cue [20]. Bodily expressions also convey information about actions taken in relation to an emotional response and leave little room for interpretation as opposed to facial expressions [6], e.g., bodily expressions of fear provide insights on the perceived threat and the action carried out in response. Such indicators are useful for design to understand underlying factors and identify areas of improvement. For this reason, bodily expressions were used in this study as non-verbal indicators of affect. Speech was also included to capture emotions and their causes as verbalized by participants. Participants' affect was coded for discomfort and conflict using either instances of speech or bodily expressions shown in Table 1 for each category.

Table 1. Instances of affect used to code trials

Discomfort	Conflict
Speech • Expressing safety concern • Requesting to stop *Body Language* • Hand waving including sudden release of joystick • Grasping arm rest • Tapping hands on armrest/table/knees • Gesturing towards knees • Sudden squeezing of legs together • Fingers stretched out in stop gesture • Clenching • Pulling back on joystick	*Speech* • Profanity • Questions about joystick operation, system action, or required user action directed at researcher *Body Language* • Looking at researcher for assistance • More than 3 incorrect joystick movements toward an obstacle • No action for more than 5 seconds (except for deliberate breaks) • Lifting up hand slowly • Pointing towards joystick

The choice of body language instances of the different emotions were informed by [3, 12, 33]. Context-specific instances (e.g. pull back on joystick) were also considered. Conflict was defined as a mismatch between user behavior or expectation and system behavior. These are instances where progress in the task was unsatisfactory: the user did not progress or disagreed with how the PWC proceeded. Instances of conflict included expressions of anger (high activation), frustration (mild activation) and confusion (low activation). At mild to high activation levels, conflict can take the form of the user becoming aggressive or doing repeated incorrect joystick motions towards an obstacle, illustrating the conflict between the user's intended direction and the system's collision prevention mechanism. The conflict at a lower activation level is more subtle; lack of system intervention or feedback can oppose the user's expectation of assistance. Discomfort was associated with safety concerns and lack of trust in the system. Instances of discomfort ranged from anxiety (mild activation) to fear (high activation). Body language minimizing the body, tapping and context-specific instances including sudden joystick release from being too close to an obstacle were counted. Single occurrences that could be either discomfort or conflict were counted only as discomfort. Often, participants verbalized issues that led to discomfort or conflict, providing context about the source of these emotions e.g., task or design related, confidence in their abilities or the system's, etc. Authors 1, 2, and 3 coded 450 videos for these instances. A subset of videos was first coded simultaneously by the authors to ensure agreement on the coding procedure. Any new type of instance of discomfort or conflict was added to the list. For each trial, the total number of instances of each category was compiled. The first author then coded videos of participant 6 and the second author coded all remaining videos. Data for participant 6 is included in the raw data, but excluded from the statistical analysis because it contained many outliers (section 3.1). Of the 9 remaining participants, videos of 5 participants were validated by the third author to ensure inter-coder agreement. The final count of instances of discomfort or conflict for each video was compared. Cases of ambiguity were discussed and a consensus was reached quickly, resulting in 100% agreement in the validated data.

3. RESULTS

3.1 Conflict

A two-way repeated measures ANOVA (3*5) was carried out to determine the effect of the three modes and five scenarios on the level of conflict. Significance is reported for $\alpha=0.05$. The data for participant 6 was removed since its studentized residuals were outliers ($\pm 3\sigma$) on many scenario/mode pairs. While ANOVAs are considered parametric tests, they are robust to violations of normality which were present in some of the scenario/mode pairs of affect counts. The assumption of sphericity was violated for the two-way interaction ($p=0.012$). There was no statistically significant two-way interaction between scenario and mode for conflict ($F(2.598,20.785)=2.754$, $p=0.075$) correcting for sphericity (Greenhouse-Geisser correction). As a result, the main effects of scenarios and modes on conflict were analyzed.

3.1.1 Variability between scenarios

Figure 1 shows the mean±SD for conflict counts across scenarios. The assumption of sphericity was correct ($p = 0.359$). There was a statistically significant difference in conflict for different scenarios ($F(4,32)=3.898$, $p=0.011$). A pairwise comparison (Tukey post hoc test adjusted for multiple comparisons using the Bonferroni method) indicated a significant difference between the table docking and back-in parking scenarios with a mean difference of -1.593 ± 0.384 ($p=0.032$). The table docking task has the lowest count of all scenarios. This may be explained by task complexity and distance to travel, reducing the total potential number of conflict instances. Participants only had to drive forwards a few meters with limited maneuvering required to align with the table. Some participants' short term memory impairment may also have played a less significant role in causing conflict due to the brevity of the task. Both the table docking and back-in parking scenarios are of rather short duration and require aligning with furniture. The higher conflict during the back-in parking task can be explained by the challenge of driving in reverse.

3.1.2 Variability between modes

Figure 2 shows the mean±SD for conflict counts between modes. The assumption of sphericity was violated. There was a statistically significant difference in conflict for different modes ($F(1.176,9.411)=19.080$, $p=0.001$) using the Greenhouse-Geisser correction for sphericity. A pairwise comparison (Tukey test with Bonferroni adjustment for multiple comparisons) revealed that increased system autonomy led to significantly reduced conflict. Inappropriate participant reactions were observed in the BS mode in reaction to the stopping behavior of the wheelchair. Due to a lack of understanding of the system, participants either took no action once the chair was stopped or took inappropriate action by continuing to push the joystick forward or by questioning why the chair was not moving forward. This is coherent with reduced conflict in the SC mode since, in this mode, the tele-operator rather than the user redirected the PWC towards free space. Conflict in SC took the form of disagreement with redirections. AD led to the least conflict. Instances of conflict with system feedback were rare, but noted in the BS and SC modes.

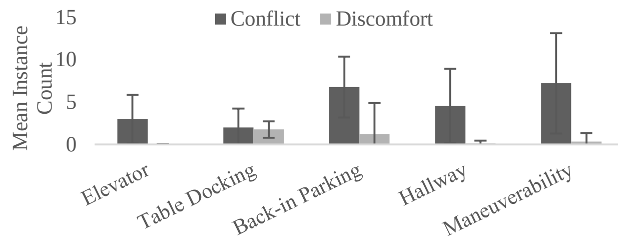

Figure 1. Affect comparison between scenarios (mean±SD)[2].

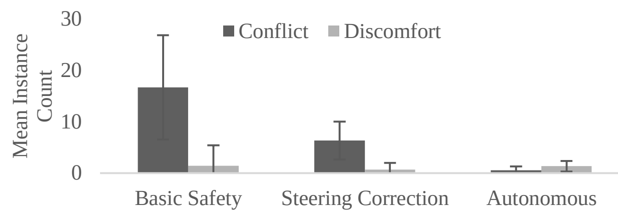

Figure 2. Affect comparison between modes (mean ± SD)[2].

3.2 Discomfort

As previously with conflict, participant 6 has very high levels of discomfort (counts ranging from 9 to 58, mean±SD: 26.3±16.9) compared to all other participants (counts ranging from 0 to 9, mean±SD: 0.2±0.9). A two-way repeated measures ANOVA was planned to determine the effect of the different modes and scenarios on the levels of expressed discomfort. Due to the few non-zero counts of discomfort, an ANOVA is not appropriate.

3.2.1 Variability between scenarios

A Friedman test was run to determine if there were differences in level of discomfort expressed between the scenarios within each mode. The level of discomfort was significantly different between scenarios in the AD mode only ($\chi 2(4)=28.000$, $p<0.005$). Pairwise comparisons between scenarios (Wilcoxon signed-rank test) were performed for this mode. There was a statistically significant median increase in discomfort by one instance of discomfort when participants performed the docking task (median of 1 instance of discomfort) compared to all other scenarios (median of 0 instances of discomfort, $z=-2.401$, $p=0.016$). No statistical significance was found between the other scenarios ($z=0$, $p=1$). Participants verbalized injury concerns in docking by either hitting unseen obstacles under the table (e.g. table leg) or by scraping their hands and knees on the underside of the tabletop.

3.2.2 Variability between modes

There was more variability in the level of discomfort expressed in BS and SC as opposed to AD, as visualized in Figure 2. A Friedman test was run to determine if there were differences in

[2] Data from participant 6 was not included.

level of discomfort expressed between the modes within each scenario. The level of discomfort was significantly different between modes in the table docking task only ($\chi2(2)$=7.760, p=0.021). In this scenario, pairwise comparison revealed a statistically significant median increase in the level of discomfort by one instance when participants drove in the AD mode (median of 1 instance) compared to both the BS (0 instances, z=-2.232, p=0.026) and SC (0 count, z=-1.983, p=0.047) modes. There was no statistical significance between the BS and SC modes (z=-1.000, p=0.317). Participants 4, 5 and 6 showed discomfort in the AD mode with being driven too close to the table. Participants who were under the impression a computer was driving the chair, expressed concern that the system had not detected the table.

4. DISCUSSION

4.1 Affect vs Participant Feedback

While the least conflict was found overall in the autonomous mode, discomfort was significantly more important in the docking task for the AD mode. Participants' rankings of modes reported in [32] indicate that the steering correction mode is the most preferred overall: the odds of participants choosing SC mode over all scenarios were 1.79 greater than the odds of participants choosing AD (p<0.05) and 2.14 greater than the odds of choosing BS (p<0.05). This discrepancy between the level of conflict associated with each mode and user-reported preference indicates other factors are at play. As reported in several user studies [15, 23, 29-32, 34], participants' desire for control is a major factor influencing preferences. Since conflict stems from mismatched user expectations/intent and system behavior, the concept of conflict is related to the issue of control. More conflict would have been expected at higher levels of system autonomy considering autonomy opposes users' desire for control. This was not the case presumably because, in the AD mode, users only had to relinquish control once on an on-going basis for the entire task and users accepted that this was how the mode operated. In the shared control modes, control was intermittently taken away from users without warning or explanation, resulting in higher conflict counts. The lack of predictability relating to control rather than the level of control in the BS and SC modes might thus be responsible for the higher conflict counts. These modes also required more decision-making than in AD resulting in higher engagement and more opportunities for conflict. The finding that BS causes the most conflict due to being stopped aligns with the user feedback reported in [24, 29, 32]. For some participants in studies with similar systems, these stops also caused frustration [31, 35]. This indicates that despite the participants having more control, more conflict arises because the user is not provided with sufficient information to make adequate use of that control. The high level of conflict observed in the back-in parking task also corroborates participant 1's comments regarding the higher degree of difficulty and unfamiliarity of this scenario [29]. The low level of conflict in the table docking scenario is coherent with participants' appreciation of being stopped before hitting the table in both BS and SC, as well as their ability to retain control to make fine adjustments at a slower, docking speed in these modes [29].

The higher levels of discomfort for the AD mode in the docking task are not as strongly reflected in participants' scenario-specific mode preferences. The odds of participants preferring BS and SC are respectively 1.23 and 2.29 greater than the odds of preferring the AD mode, but these values are not statistically significant [32]. The higher level of discomfort associated with the AD mode due to a fear of injury corroborates participants' comments voiced in the post-trial and post-study interviews [24, 29] and their expressed desire for control due to safety concerns [29] as well as potential users' concerns including a lack of trust in the system's capabilities over their own [16], and the inability to override a system decisions in unsafe situations [34]. Potential users are not always distrustful of intelligent PWCs as reflected by a lack of discomfort in other scenarios and modes. They would use the AD mode due to a lack of trust in their own driving abilities when faced with challenging situations, or when too tired to drive [29].

4.2 Implications for Design

4.2.1 Control Modes

Both autonomous and shared control modes may be preferred by users based on circumstances. To reduce conflict in shared control modes, seamlessness and predictability must emphasized in the integration of the user's input. Integrating the driver's input during system interventions would make for a smoother transition. Such an approach would eliminate the full stops which generated much frustration in the basic safety mode. The CARMEN system achieves seamless transitions by continuously blending user and system inputs by assigning weights based on punctual driver and system performance [28]. If discrete system interventions are preferred, the user can be assigned full control and, when needed, a smooth step function can be applied to gradually shift from user to system commands. In cases where the system has computed an optimal path to follow, the elastic band method has also been used to provide a smooth shared control driving experience [4, 37]. An improved AD mode should address safety concerns by increasing user control by allowing tasks to be aborted or overridden. The ability to add specific way points is suggested for PWC designs with higher levels of automation [15].

4.2.2 System Feedback to User

Reducing conflict by increasing the predictability of the PWC's interventions in both shared control and autonomous modes may also be achieved by improved real-time feedback. Conflict due to a lack of understanding of system interventions can be alleviated by offering richer feedback about the location and proximity of obstacles, as suggested in [29]. Low activation conflict or confusion caused by the stopping behaviour in the basic safety mode could be reduced by prompting the user to redirect towards free space. Audio prompts were offered in some systems with varying adherence [13, 31]. Further research needs to be conducted to determine the best modalities and content to improve driving performance and reduce conflict. To alleviate discomfort, functionalities that perform at a high degree of autonomy and require approaching objects or people should be designed to mitigate the higher potential for fear of injury. For table docking, this may be possible by reassuring the user that the table has been detected by using sensory feedback, by having the PWC pause momentarily and reduce its speed, or return control to the user before engaging into the final docking move.

4.2.3 Adaptability

The results of this study support previous studies' conclusion of the need for a system capable of being adapted or self-adapting to both users and context [13, 16, 28, 29, 31, 34]. In the docking task, some participants' discomfort with how close the tele-operator drove the PWC to the table revealed the need to customize the minimal stopping distance to furniture, obstacles or people. Participants' annoyance with the audio feedback versus other participants' requests for more informative feedback also illustrates the necessity to consider individual preferences. The system must also adapt how control is shared with the user and what feedback is provided based on the context due to the varying level of affective response to the different scenarios. For instance, the back-in parking task might benefit from prompts to help users reverse or an automatic switch in joystick signals so that the PWC reverses in the same direction as the joystick is moved. In the case of table docking, it is rather fear that the system could address using the strategies outlined in the previous section. Automated affect analysis could provide real-time feedback on the user's interaction with the system. Machine learning methods could be leveraged to improve and tailor the user experience accordingly.

4.3 Challenges and Limitations

Analyzing affect, particularly conveying intensity and duration of emotional expression, can be challenging. Occurrences of emotional expression were simply counted but, in some cases, participants would do the same movement continuously or repeatedly. A single, continuous occurrence was counted once while repeated occurrences were counted as distinct occurrences. The intensity of instances were not considered, but may be important in interpreting results. When analyzing body language, the use of computer vision or wearables to quantify the speed and amplitude of movements may allow for further insights. A galvanic skin response sensor was used, but its lack of robustness to movements and displacement by participants resulted in unusable data. The use of wearables should account for participants intentionally or inadvertently displacing them. Since confusion and agitation are expected among people with cognitive impairment, some of the instances of conflict may be related to their cognitive state rather than the PWC. The design of technology for older adults should consider the individual as a whole, including impairments [22]. As such, all counts of conflict were considered, whether related to PWC use or not. While body language and speech convey meaningful information, the addition of facial expressions may have provided further insights. Future work will include both facial and bodily expressions of affect. Due to the sample size and variation in participants' abilities, some usability issues may not have surfaced [18]. Nonetheless, this study has helped identify key aspects of the system to improve and inclusion of real users in naturalistic environments is critical in ensuring future adoption by the target users. Since a human tele-operator was used to mock-up the system, it can be expected that participants' affect may be different knowing that a human rather than a machine was in control. Whether or not participants were aware of the tele-operator's role (which was unclear from their comments), reactions to the system may have differed due to the inability of a human operator to perfectly mimic an intelligent system's behavior. Researchers' presence may have also altered their perception of safety or caused performance anxiety. Trials were limited in duration to five days plus training, limiting participants' ability to become familiar with the technology and form long-term impressions. Future studies may benefit from more discrete researcher observation and intervention as well as a longer trial period.

5. CONCLUSION

Older adults with cognitive impairment displayed conflict but little discomfort when driving a mock intelligent PWC under different control modes. Conflict was lower for higher levels of tele-operator interventions. Discomfort was uncommon except in the table docking scenario for the autonomous mode, due to fear of injury. Affect analysis of real-time speech and gestures corroborates results from the semi-structured interviews and questionnaires, while also allowing us to quantify and compare results across modes. The ability to gather information while participants are driving without distracting them can provide unbiased data on the user experience especially when participants may have difficulty recalling their perceptions of the technology after the trials. Results are informing the design of table docking and feedback modules, to be validated with this population.

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