See-Thru: Towards Minimally Obstructive Eye-Controlled Wheelchair Interfaces

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ABSTRACT

Eye-tracking interfaces increase the communication bandwidth between humans and computers when using hands is not possible. For some, eyes are the only available input modality to control and interact with the various devices that enable their independence. The goal of this work is to develop and evaluate an eye-controlled wheelchair navigation interface that minimizes obstruction to the user's field of view by removing the conventional use of a computer screen as a feedback mechanism. We present *See-Thru*, an eye-tracking interface that provides feedback to the user without a screen while simultaneously providing a clear view of the path ahead. Our prototype is evaluated against a screen-based state of the art interface in a study with three navigation tasks completed by seven power wheelchair users. Our results show that a majority of the participants not only prefer using the See-Thru interface, but perform better at driving tasks when using it. This supports the notion that users favor minimally obstructive interfaces in navigational contexts.

Author Keywords

Eye Gaze; Eye Tracking; Gaze Control; User Interfaces; Power Wheelchair; Navigation; Field of View (FOV)

ACM Classification Keywords

- **Human-centered computing ~ Human-Computer Interaction (HCI);** Accessibility; Interaction techniques
- Social/Professional Topics ~ Assistive technologies

INTRODUCTION

Eye-tracking is the process of estimating a user's gaze, or where a user is looking. Eyes and their movements have long been studied for their communicative importance in conveying a person's needs and emotions [10], as well as their strong indication of attention and intent [23]. In particular, researchers have explored gaze-tracking in the context of interaction. One vein of this research has resulted in the design of personal gaze-based devices that allow users with "locked in" neurodegenerative diseases or other severe motor disability to interact with the world with a transformative level of independence and autonomy.

Figure 1. The See-Thru interface mounted onto a power wheelchair.

The design requirements for these eye-gaze interfaces are substantially different from traditional human-computer interfaces because both command execution and feedback observation tasks are performed by human eyes simultaneously [1]. As most of these applications are designed to enable users to interact with computers, the user interfaces generally rely on robust screen-based feedback to help navigate between various execution and observation tasks.

When used in the context of driving a wheelchair, the design requirements become even more complex. Specifically, this is due to the highly dynamic nature of the application in which the user must simultaneously watch where they are going and engage with their gaze-enabled interface. The added task of evaluating the path ahead is arguably just as important as controlling the eye-gaze interface itself, yet most conventional eye-controlled wheelchair implementations require users to interact with an obstructive computer monitor that is mounted directly in the center of their field of view (FOV). While mounted monitors are indeed useful for both relaying feedback and limiting the amount of false positives by restricting gaze input commands within the screen boundary, they prevent users from having direct visual access to their surroundings. This obstruction reduces the feedback that users can gather from the changing environment.

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Despite these design challenges, portable gaze-controlled devices that are capable of maneuvering power wheelchairs hold the promise to greatly increase the independence and quality of life for those living with severe motor disability. As advancements to eye-tracking research and technology works towards creating realistic, consumer-available systems, it is essential that their designs are not only functional, but robust, intuitive and user-friendly.

This paper proposes a novel gaze-based interface for wheelchair control that addresses the design challenges of a visually obstructive screen-based feedback mechanism (Figure 1). Our prototype replaces a computer screen with a see-through wire-frame device that contains a small set of spatially arranged LEDs that serve as both gaze targets and status indicators. The space in between LEDs is open, so that users can simultaneously observe the environment during navigation. In order to prevent unintended movements of the power chair, users must consecutively activate a short set of specific gaze regions to switch in and out of two main system states: Drive and Rest. We describe the implementation of this system and report on feedback from seven users who successfully completed several wheelchair navigation tasks with our technique.

RELATED WORK

Current eye-tracking devices draw from a varied repertoire of hardware sensing platforms and detection algorithms. We review only the most relevant methods related to our work. This section also details a few examples of current state of the art gaze-controlled wheelchairs that have served as an inspiration to the novel eye-tracking interface presented in this work.

Eye-Tracking Methods

Within the literature, most eye-tracking methods can be generally divided into two main groups: those measuring the angular eye position relative to the user's head (through a head-mounted sensor), and those measuring eye position relative to the world (through a sensor mounted in the environment) [19]. The first method is especially interesting because it enables gaze-detection in a mobile context by providing more freedom to adjust one's seating position without compromising the sensor accuracy. Unfortunately, such head-mounted systems are expensive due to their small market size, currently costing upwards of 12,000 USD, and are therefore prohibitively expensive for the average user. One exception, however, is that of Pupil Labs head-mounted eye-trackers, which have a price point of around 1,500 USD [9]. On the other hand, eye-trackers that measure absolute eye-position relative to the sensor's placement have become increasingly affordable, like the Tobii Eye Tracker 4C used in this research (see Figure 2), which costs only 150 USD. Regardless of the form factor, these sensing platforms operate with similar underlying principles in order to produce their measurements.

Video-oculography (VOG) works by tracking visible features of the eye – such as the pupil, iris, sclera – or reflections on the surface of the eye – corneal reflection [15]. Gaze direction is estimated by processing images recorded by a video camera, either in a remote table-top system [4, 19], as shown in Figure 2, or on a head-mounted system [3, 12, 14, 17]. Many systems that are interested in gaze point measurements on a user interface measure eye position relative to the surrounding environment rather than the user's head position. These methods typically use IR light for illuminating the eye, and/or IR cameras for detection because the uncontrolled ambient lighting used as the light source in visible spectrum imaging [5] can add noise and unpredictability to the system.

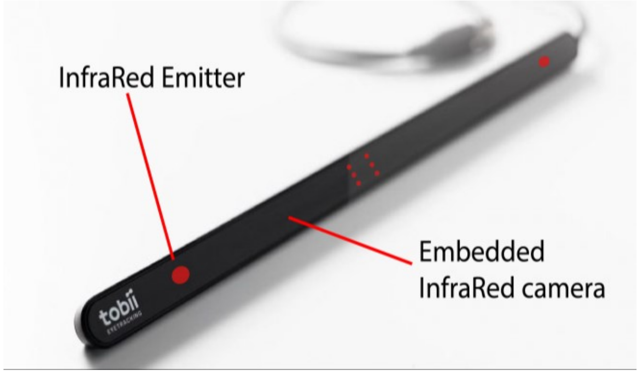

Figure 2. Tobii Eye Tracker 4C sensor before mounting to a computer.

Eye-Tracking User Interfaces

Gaze can be much faster at indicating intent than conventional methods, such as a manual computer mouse. Gaze not only shows where current visual attention is directed, but it also precedes human action, meaning that we look at things before acting on them [17]. As such, a key challenge involves designing effective interfaces that can successfully exploit this potential. This section discusses only a couple of the most fundamental interface designs found in conventional eye-tracking systems. The following techniques comprise the basis upon which our proposed prototype has been implemented.

Gaze Regions

Active gaze regions are one of the simplest techniques to replicate mouse clicking in eye-tracking applications. Gaze regions are software-defined zones on a digital screen that are linked to specific pixel boundaries. When an eye-tracking system detects that a user's gaze has entered into the pixel boundaries of a particular gaze region, a unique action can be triggered automatically.

As mentioned previously, using gaze as an input method can introduce many diverse problems, since the eyes are used for both sensing and control. Most notably, systems need to be able to prevent the "Midas Touch" problem, in which all items viewed are selected [7] without the user intending to do so. There has been considerable research that has implemented and tested various methods to do just that over the years [22]. For systems that incorporate eyes-only interaction, the most common method used to prevent mistaken activations is to use a short delay period, known as a "dwell time", which differentiates observation from intended control commands. It works by displaying feedback to the user for a pre-defined period of inaction immediately after a user's gaze falls on a selectable gaze region. Given this feedback, users have the option to maintain their gaze until the period of inaction ends or to cancel the action by looking elsewhere. This consideration enables a much more usable interaction pattern when dealing with a screen interface with multiple active gaze regions because it allows the user to examine the possible selection options without immediately activating anything. Dwell time can vary depending on the skill level and responsiveness of a user, but generally longer dwell times can be uncomfortable and tiring. Majaranta et al. devised a system to navigate this issue by allowing the possibility to adjust dwell time, which increased user satisfaction [16].

Importance of Feedback

A further area of concern is that of sufficient feedback in an eye-tracking interface. In an overview of eye-tracking in advanced interface design in 1995, Jacob noted the important role of feedback in gaze interaction, specifically with the use of a cursor indicating the location of the user's gaze [8]. Users generally know where they are looking, but not with a pixel-by-pixel accuracy. Also, slight calibration errors can give rise to discrepancies between where the user is looking and where the system thinks the user is looking, so visual feedback helps to bridge this gap. Even if an eye movement-based system does not incorporate a cursor or some other method for feedback of the user's focus, feedback is still relevant for selection purposes in indicating whether the system has selected the intended object.

One example is that of animated feedback of the progression of dwell time, which helps users maintain their gaze on the desired object long enough to avoid premature exits [6]. This method works on top of highlighting gazed-upon objects on a screen, which helps the user verify that the system is actively aware of the location of their gaze [18] (see Figure 3).

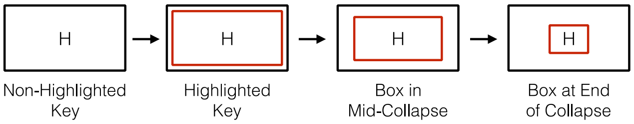

Figure 3. Animated gaze component highlighting. Redrawn from [18].

Eye-Controlled Wheelchairs

Driving a power wheelchair with only eye movements necessitates a robust system capable of quickly detecting user intention while simultaneously providing control over many degrees of freedom. For people living with severe mobility challenges, these eye-controlled wheelchairs must incorporate an interface that is unobtrusive, easy to use, responsive, versatile and affordable (among other metrics that contribute to user satisfaction) [15].

Figure 4. An example of a conventional eye-controlled wheelchair design made by Microsoft Research.

Although many interaction techniques we have mentioned so far are sufficient for conventional eye-tracking environments, research shows that wheelchairs encounter situations that are much more dynamic [11]. Specifically, successful systems must design for users that are actively paying attention to both the environment through which they navigate and their eye-tracking interface. This means that these systems must consider the constant movement and changes in both body positioning and lighting conditions that are a natural part of navigating through real-world environments [20]. A majority of the research involving eye-controlled power wheelchairs concerns itself with the implementation of gaze-based interfaces that incorporate dwell time interactions with on-screen gaze regions that map to wheelchair motor controls (Figure 4). For instance, Barea et al. developed one of the first gaze-driven power wheelchairs with a simple graphical user interface (GUI) composed of four gaze enabled buttons that mapped to directional control of the wheelchair's motors [2]. Each button, represented by an arrow pointing either up, down, left, or right, increases the speed of the chair in the direction corresponding to the selected button.

One shortcoming of this system is that no matter where a user looks, their eye movements will initiate an action of some sort, which can become strenuous and fatiguing for the user. Furthermore, Barea's prototype only allowed for one-way communication through the interface, meaning that no feedback was presented to the user, depriving them of any cues as to how the system interprets their eye-movements. Further still, this implementation requires a screen for user interaction, but this obstructs the user's field of view (FOV), which makes natural navigation even more challenging. As can be observed from the literature, this obstruction is a common challenge shared amongst nearly all implementations built around a screen-based GUI.

In recognition of the fatigue brought on by activating a motor control command no matter where the user's gaze lands on the interface, Lin et al. proposed a novel GUI that divided the screen into 9 regions, 4 of which are gaze contingent command regions while the remaining 5 regions are idle zones that allow the user to rest their gaze without any activation (see Figure 5) [13]. Just like the previous implementation, however, this system presents no visual feedback to the user.

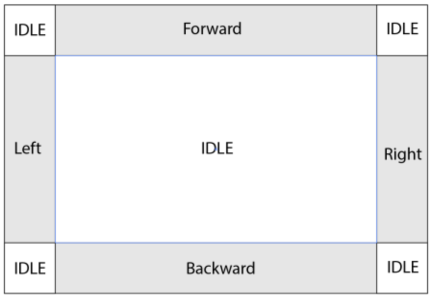

Figure 5. A gaze interface with idle gaze regions developed by Lin et al. Redrawn from [13].

Once a user activates a command by gazing at one of the 4 active regions, the central idle space will expand and absorb the recently activated command region, effectively providing 'invisible' feedback as to which command is being executed by temporarily rendering it an idle zone. This GUI design allows the user to rest while still carrying out a navigation action, which provides much more natural interaction for the user. There is still, however, the inherent issue with the visual obstruction of the screen display blocking the user's FOV during navigation.

Wästlund et al. devised an interface that aimed to both provide adequate feedback to the user and reduce the inherent obstruction of the screen in use [21]. Similar to Barea's work, their solution consists of a gaze-contingent dynamic interface that can visually change its layout in response to gaze commands issued by the user. Unlike previous prototypes, however, this interface is overlaid on top of a live webcam stream of the view immediately in front of the screen so that the user can watch the screen to both interact with the GUI and to keep an eye on where they are going (see Figure 6). The GUI consists of four directional control buttons, with active highlighting of the currently selected button to give visual feedback to the user that indicates which command is currently activated.

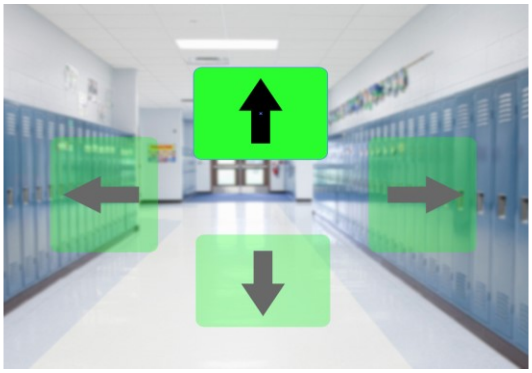

Figure 6. Live video stream of the environment in front of the wheelchair with gaze components overlaid. Redesign from [21]

Virtually all other state of the art gaze-driven wheelchairs involve a similar GUI design as this one proposed by Wästlund et al., whereby a live video stream is used to work around the inherent obstruction posed by the use of a computer screen. Although this video stream is a clever way to allow the user to see behind the screen, it can feel disorienting because it does not fit neatly into the user's understanding of the scene around them. On top of their own perception of the environment through their eyes, the user must mentally process the wide-angled view of the path ahead through the digital screen. This introduces a large margin of visual overlap that is both redundant and confusing to reconcile.

IMPLEMENTATION

Although we have pointed out their shortcomings, the design of the eye-controlled wheelchair used in this work is heavily influenced by the prototypes developed in the research discussed above. Similar to previous implementations in the literature, our physical apparatus is built around a Tobii Eye Tracker 4C, which communicates with a program running on a Windows tablet. When the user's gaze fixates on a gaze-activated region defined by the program, a control event is triggered, which sends a drive command to the wheelchair and updates the LEDs embedded within the "wire-frame" interface device to relay feedback to the user (see Figure 7).

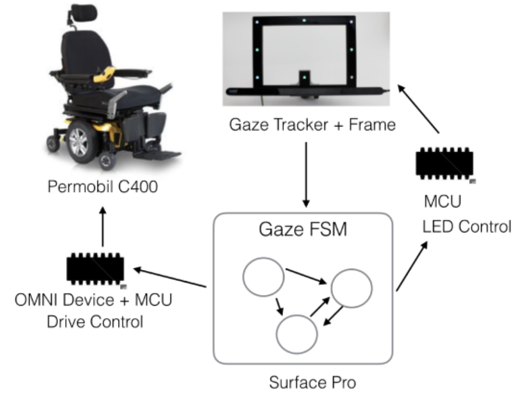

Figure 7. System diagram of the See-Thru prototype.

The system created for this research was developed using standard RNET software, which many wheelchair manufacturers use to control their products. This allows the system to interface with native controls and enables users to easily switch between the default joystick control mode and our gaze-controlled mode. Specifically, we use a Permobil C400 power chair with an OMNI controller.

Wire-Frame Interface Device

We use a gaze tracker mounted to an acrylic frame that has feedback LEDs embedded along the perimeter, but is transparent in the middle. The LEDs are used as gaze targets and provide visual feedback, while the wheelchair user can also still look through the frame to observe the environment they are navigating (see Figure 8).

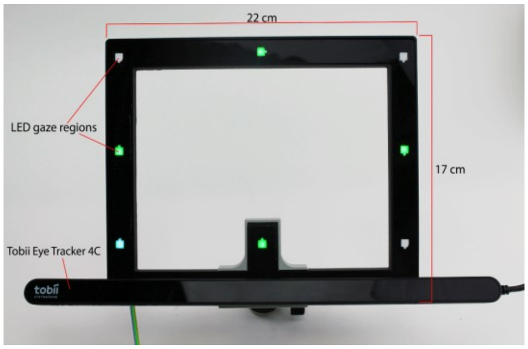

Figure 8. The wire-frame interface device in the Direct Drive State with a Tobii Eye Tracker 4C mounted on it.

The acrylic frame is designed to be about the size of the screen that the Tobii Eye Tracker 4C is calibrated to. Each LED is programmed to change color depending on the current state of the system. For instance, in the Drive State, a green LED indicates that the wheelchair will move in the respective direction if the user fixates their gaze on it. Once a particular green LED has been fixated on, the wheelchair begins to move and the other LEDs turn red. A red LED indicates that, if fixated upon, the wheelchair will stop whatever action it is carrying out and return to the default Drive State configuration (see Figure 9). A cyan LED represents the first part of the clutching sequence that is required to switch between Rest State and Drive State.

Further, each LED is capable of *active highlighting*, whereby they will increase their current brightness if a user's gaze lands on them in order to communicate that the system is aware of the location of their gaze. Lastly, each gaze-enabled LED region can only be activated after a defined *dwell period*, during which the user must constantly maintain their gaze on the desired region. If the user's gaze is maintained for the entire duration of the *dwell period*, then the system will trigger the appropriate response associated with the respective gaze-enabled region.

The wire-frame serves as a "transparent stand in" for the computer screen, and the LED feedback actuators serve as physical representations of the digitally defined gaze-enabled buttons (see Figure 8).

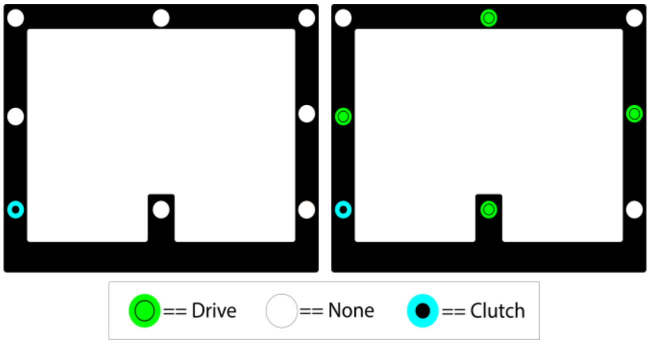

Figure 9. ***Left:*** **Rest State diagram.** ***Right:*** **Drive State diagram**

To calibrate users to the system, we use the default Tobii calibration software, but instead of showing the usual screen, we use a piece of paper that has calibration targets drawn in the same locations. This paper is physically placed on top of the frame during calibration so that the drawn-on targets overlap directly above the location of the digital targets (that is, if the usual computer screen were present). For this paper, we did not implement a new calibration routine using only the frame, but this could be a goal of future work.

Although our software runs on a Surface Pro, the device is stored out of sight as to avoid obstructing the user's FOV.

Finite State Machine

Each state in the system's FSM serves a unique function, and the system exposes "clutching" controls to allow the user to switch between them at will (Figure 9 and 10).

The Rest State is the simplest state in the FSM and it serves as an inactive state where the user's eye movements are not capable of triggering any drive commands. This affords the user the option to attend to the world beyond the eye-tracking interface without having to deliberately avoid looking at it. In this way, the user's gaze may unintentionally land on the interface and nothing will happen. The Rest State consists of only one gaze-enabled LED region positioned at the bottom-left of the interface.

This LED serves as the initial "clutching" control that is used to step into the Drive State. The remaining 6 LEDs regions are turned off to convey their inactive status.

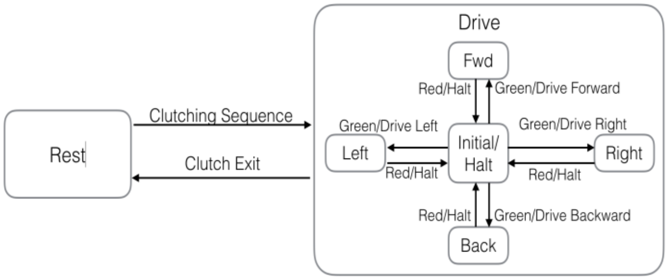

Figure 10. Diagram of the See-Thru finite state machine.

The Drive State comprises 4 main directional drive regions and a single clutch LED. The drive regions adhere to the following convention: The Top-Middle gaze region maps to Forward Drive, Bottom-Middle maps to Backward Drive, Left-Middle maps to Left Drive and Right-Middle maps to Right Drive. The state clutch LED is activated by gazing at the Bottom-Left gaze region. The directional drive LEDs are initially green to indicate that gaze-based activation will result in actuation of the power wheelchair's motors in the respective direction. The clutch LED is cyan in order to be easily distinguished from the green drive regions. This clutch region allows the user to switch back into the Rest State when the navigation task is complete. When a gaze-enabled directional drive command region is activated, the wheelchair will begin to move. Also, the interface will

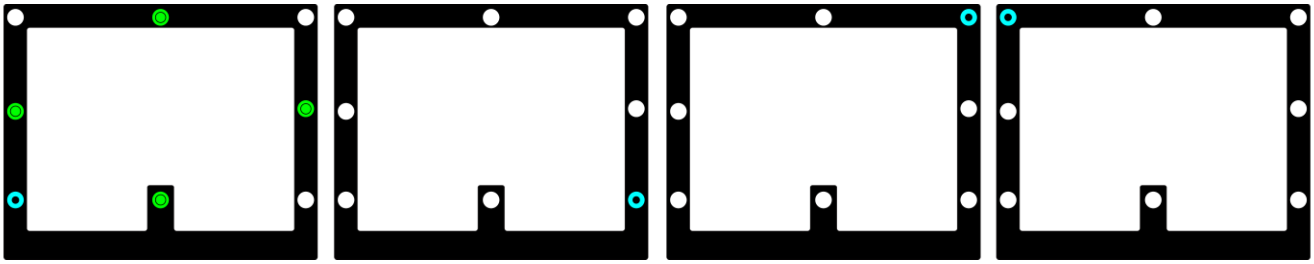

Figure 11. A full clutching sequence starting from the Drive State when the user fixates on the bottom-left gaze-enabled zone. After activating the last gaze-enabled clutch region, the system will be back in Rest State.

change its layout so that the 7 remaining LEDs become red, indicating that the wheelchair will be halted if they are activated next.

Clutching Mechanism

The system's clutching mechanism consists of a feedforward sequence that begins when the user fixates their gaze on the initial color-coded gaze-enabled LED (see Figure 11). After the initial clutch region is activated, all of the gaze-enabled LEDs in the interface turn off except for the next LED in the sequence. The sequence consists of 4 consecutive LED activations placed strategically around the interface so that only clearly intentional eye-movements are capable of switching states. If the users gaze fixates on an inactive LED at any point during this clutching sequence, the system will return to the most recent state before the clutching began.

RESEARCH GOAL

We hypothesize that the minimal design of our wire-frame device will allow users to control their wheelchair with greater ease compared to the status quo of screen-based interfaces because they can gaze naturally at their environment, unencumbered by a visually distracting monitor. The goal of this work is to evaluate this prototype and show that it is not only as functional as the state-of-the-art screen-based implementations, but that it is in fact the preferred choice when given the option.

Although using a screen for gaze-controlled wheelchair navigation has been proven to be successful, we find that the combination of gaze feedback overlaid on top of a live video feed of the path ahead is a potentially poor match for the navigation task itself.

Specifically, prior systems incorporate a video feed to work around the fact that the feedback monitor severely obstructs the user's FOV. We find this complication unnecessary and even confusing for the user because the display still potentially occludes their FOV and may be visually distracting due to the brightness and the spatial disconnect between the video and the real world ahead. Thus, these systems require users to balance their visual attention between the direct environment in their periphery and the wide-angled, digital representation of the environment in the rectangular screen-display before them.

Our proposed interface differs from prior screen-based wheelchair gaze controls by removing the screen. While a fixed transparent frame is less flexible than an LCD display, we hypothesize that wheelchair users may prefer it to screen-based solutions because it provides them with better visibility of the environment.

RESEARCH METHODS

In order to evaluate the See-Thru prototype, we conducted a between-subjects navigation experiment. The experiment was conducted with seven wheelchair users. In this section, we discuss the details of both the experiment and the data that was collected from each participant.

Participants

The prototype was tested with seven individual power wheelchair users, each with varying degree of disability. It should be noted that only two participants, who we will refer to as P2 and P5, controlled their wheelchairs via a hands-free interface, while the remaining participants were able to navigate their wheelchairs using a standard joystick module. Specifically, P2 uses head array switches to control their wheelchair, while P5 uses a miniaturized joystick that is controlled by their bottom lip and jaw movements.

The participants that volunteered for this study live with a variety of different disabilities including systemic mastocytosis (SM), spinal muscular atrophy (SMA) type 2, cerebral palsy, Dwarfism, Scoliosis, and C4/C5 vertebrae quadriplegia. Progressive disabilities, such as SM and SMA, will eventually necessitate the use of alternative input modalities (like eye-movement) as control of the motor system degrades. As such, the participants in this trial make up a subject population that is representative of potential users of this type of system in the future, meaning that their feedback is important for improving the designs of such an interface.

Regardless of the type of disability, each participant was able to successfully complete every navigation task using both interfaces. For most participants, this was their first time ever using an eye-tracker, let alone driving a power wheelchair with just eye movements. The success found in the driving tasks verify that our proposed interface can not only be used to safely control a power wheelchair, but can be quickly learned by user's who have no prior experience with eye-tracking systems.

Figure 12. The wheelchair used for this research, with the See-Thru prototype mounted on the left side.

Experiment Design

We evaluate our wire-frame interface against a screen-based control built with the same FSM and gaze-tracking interaction scheme.

The study consisted of one main experiment with two conditions, which compared the performance of our See-Thru interface (see Figure 12) to a screen-based control condition (see Figure 13). The screen-based control is designed around the same gaze-control scheme as the wire-frame interface, but in place of the frame, we mount an LCD screen that displays a live video stream beneath the color-coded gaze-regions.

Each experiment consisted of a series of three unique *eyes-only* navigation tasks (see Figure 14). Each task required that the user start in the Rest State and then clutch into the Drive State once the task began. Before beginning the experiments, each participant was trained to use the interface, which consisted of a walk-through of the system's FSM along with a practice drive lasting roughly 5 minutes.

Figure 13. The screen-based interface used as a control in the experimental study.

Task 1 had the participants use the Drive State to drive the power wheelchair forward in a straight line for 21ft, then backwards for 16ft, all without driving outside demarcated boundaries that were 5.5ft wide made of blue tape. The length and width values were used to simulate driving down a hallway, or wide sidewalk.

Task 2 had the participants use the Drive State to navigate the wheelchair along a curved path approximately 5.5ft wide and 48ft long, with a 180 degree turn at the midpoint, all without driving out of bounds. The curved path was designed to represent simple obstacle avoidance.

Task 3 had the participants use the Drive State to navigate in a "figure 8" pattern around 2 obstacles placed 7ft apart in order to test fine steering control. This task had no boundaries.

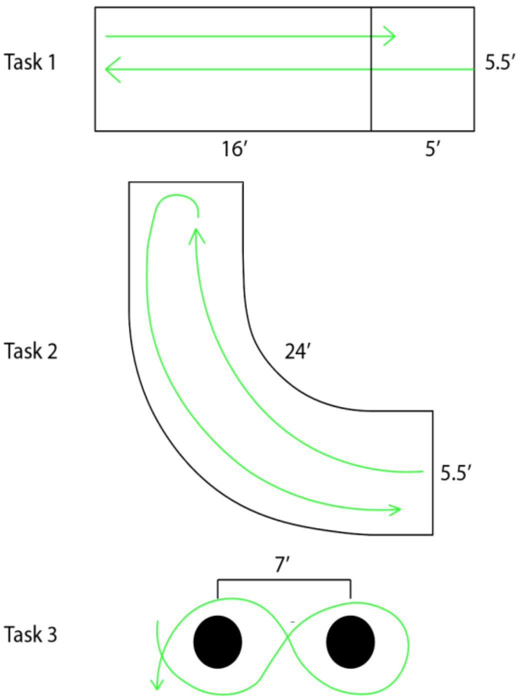

Figure 14. A visual diagram of the three navigation tasks carried out in each experiment.

Evaluation Methodology

We conducted a randomized within-subject study where participants were asked to use both interfaces to complete each task. We alternated the order of the interfaces between participants so that we could prevent any bias in the data reflecting better performance when using the second interface simply because they had more time to practice using the first interface.

For each participant, there were a number of outcome variables that were gathered to help us determine the performance of See-Thru as compared to the screen-based control. We gathered 3 main quantitative variables:

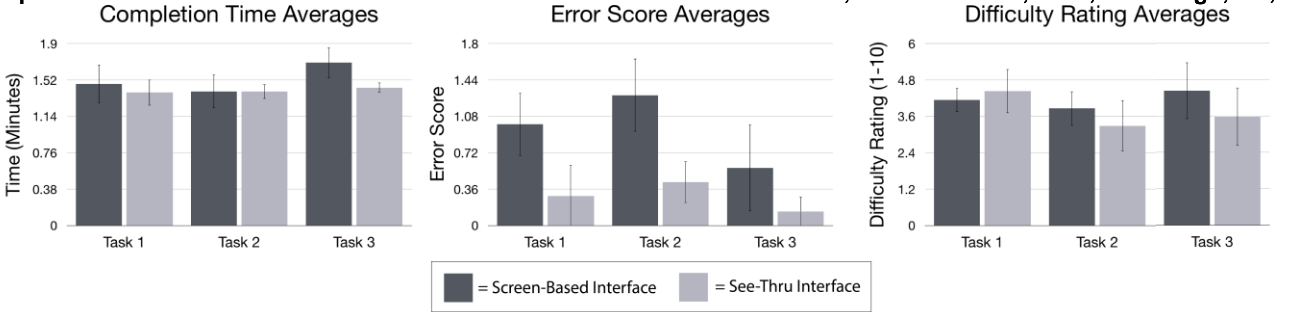

Figure 15. Error bars show +-1 standard error. *Left:* A graph depicting the average time it took to complete each task across all seven participants using the screen-based control and the See-Thru interface. *Middle:* The average difficulty rating assigned by the participants to each task after completion – 1 corresponds to the easiest rating, while 10 is the most difficult. *Right:* The average error score that was calculated for each interface across all three tasks – a lower error score corresponds to a better driving performance.

- *Completion Time:* Each task was timed from start to finish.
- *Difficulty Rating:* Participants were asked to rate the perceived difficulty of each task on a Scale of 1 through 10 – 1 representing the easiest level of difficulty and 10 representing the most challenging.
- *Error Score:* A note was made of any instance in which the participant made a driving error. Each error resulted in a 1-point addition to a total Error Score starting at 0. Possible errors include: Driving out of bounds at any point during the task; Ending a task outside the boundary lines; Bumping into the obstacles from Task 3.

After gathering these quantitative data from all participants, we took the average of each outcome variable and measured the change between values corresponding to tasks completed using the See-Thru interface and the control.

On top of these objective data points, we also made note of any qualitative comments made by the participants regarding their experience using the eye-controlled wheelchair interfaces. Finally, at the end of each session, we conducted a semi-structured interview in order to ascertain more information about the participants and their subjective opinion regarding their experience using both interfaces. During this time, we asked each participant if they had a preference for one interface or the other, regardless of their performance during the experiments.

RESULTS

For both interfaces, we calculated the average values for each of the quantitative outcome variables (time, difficulty rating, and error) as they were observed for each individual navigation task across all 7 participants (Figure 15).

Course completion times for the three navigation tasks were comparable between the two conditions, with the See-Thru condition being slightly faster than the screen condition in two out of three tasks. However, none of the observed differences were statistically significant (paired t-Test, p>0.05).

In Task 1, participants using See-Thru were on average 5.7 seconds faster (mean=1.39 min, sd=0.36) than when they were using the screen (mean=1.48 min, sd=0.65). In Task 2, average times differed by less than one second (See-Thru: mean=1.40 min, sd=0.20; Screen: mean=1.40 min, sd=0.46). In Task 3, participants using See-Thru were on average 15.6 seconds faster (mean=1.44 min, sd=0.13) than when they were using the screen (mean=1.70 min, sd=0.42).

For all tasks, participants made fewer errors with See-Thru than with the screen, but not all differences are statistically significant, likely due to the small sample size. For Task 1, participants made an average of 1.0 error with the screen interface, and 0.29 errors with See-Thru (p>.05, paired t-test). For Task 2, they made 1.29 errors with the screen interface, but only 0.43 with See-Thru (p<.05). For Task 3, they made 0.57 errors with the screen interface, but only 0.14 with See-Thru (p>.05). This indicates that users were able to navigate with slightly fewer errors when using our prototype.

Subjective ease of use ratings for the three navigation tasks were comparable between the two conditions for tasks 1 and 2; the observed differenced were not statistically significant (paired t-Test, p>0.05). For Task 3, the figure-eight pattern, See-Thru was judged to be easier (mean=3.57, sd=2.52) than Screen (mean=4.43, sd=2.46), with this difference approaching statistical significance (t(6)=2.12, p=0.08).

Thus, the main finding is that task completion times and ease of use ratings are comparable between the two conditions, but that users make fewer mistakes in the navigation tasks if they use See-Thru. We cannot yet establish conclusively why this error rate is lower, but one possible explanation, supported by some of the qualitative feedback, is the spatial disconnect between what's shown on screen and the actual environment the user is navigating in.

Qualitative Results

After concluding both experiments, participants were first asked if they had used an eye-tracking system before. All participants except P3 and P5 had never used an eye-tracker before (P3 and P5 had both tested our system in preliminary tests before this study). We then asked the following three questions.

Question 1: Did you find it easy to learn how to control the See-Thru navigation interface?

All seven participants agreed that it was easy and fun to learn. Each participant was able to start driving the gaze-enabled wheelchair independently within minutes of being introduced to the system.

Question 2: Would you consider using this system See-Thru in real life?

There was a general consensus that using a gaze-controlled wheelchair in a crowded public space seemed unsafe without smooth floors and a good amount of training. P6 was an exception to this consensus as they claimed they would want to use the system in public, as is. However, virtually every participant said they would consider using the See-Thru interface in a more private environment (i.e., at home) if they were unable to control their power chair using the current apparatus that they have grown accustomed to. P2, who lives with congenital (athatoid) cerebral palsy, expressed immediate interest in the system, claiming it was already easier for them to drive than their current navigation system (a set of Adaptive Switch Laboratory (ASL) head array switches).

Question 3: Which interface do you prefer using – the screen-based system or the See-Thru device?

Four out of the seven participants listed a preference for the See-Thru interface, while another two had no preference, and only one participant preferred the screen-based control interface. All four participants who preferred navigating the chair with the See-Thru prototype cited the lack of a screen to be helpful in that it allowed them to view the world ahead more naturally, without the distraction of a screen in front of them. Also, both P5 and P6 mentioned how the wide-angle of the computer's video feed did not align properly with the actual view of the environment that was blocked by the screen, creating an awkward "mismatch" in their perception of the obstacle course. P5 also mentioned how they felt "super focused on the screen rather than [their] surroundings" simply because there was a video feed to attract their attention. P3 stated, *"I kept feeling super focused on the screen rather than my surroundings because...I had a bright, distracting screen right in front of me."* P3 continued by mentioning that the screen-based interface made them feel "slightly claustrophobic with the screen placed directly in front of [their] face", and they liked how the See-Thru interface didn't block their immediate FOV as much.

The participants who had no overall preference also enjoyed the lack of a digital screen when looking at the path ahead. However, they mentioned that the feedback on the screen was easier to see as it updated, which made it easier to understand how the system recognized eye movements.

The sole participant who preferred the screen-based interface mentioned they liked the fact that the wide-angle video was redundant and displayed more of the environment than what was actually blocked by the screen itself. They said that they prefer to see more of the environment in front of them as opposed to using the See-Thru prototype, whose frame still blocked some of their view, even if by just a small amount. This subject qualified their preference by mentioning that a thinner frame (e.g., an actual "wire-frame") with a larger perimeter would be the best option, but until then the screen worked best.

DISCUSSION

Our proposed See-Thru interface was generally well-received and easy to learn by all participants. This is important for potential users because a steep learning curve may serve to discourage them from committing to using new navigation systems. As mentioned in the results above, completion times and difficulty ratings are comparable between the two conditions, but it is clear that participants made fewer mistakes while driving when using See-Thru. This shows that our prototype is not only easy to pick up, but it also objectively performs at least as good, if not better, than the current state of the art implementation.

The slightly quicker average task completion times that were observed when using the See-Thru interface represent the ability of the participants to drive at more preferred speeds. This shows that our proposed interface could be a more practical option when navigating through realistic scenarios because participants were able to get from point A to B without having to waste as much time on figuring out how to properly control the system. Additionally, it is important to note that the participants rated using our interface prototype as generally similar, or slightly easier than, the screen-based control. This perceived ease-of-us is crucial in helping to reduce the sensation of fatigue when using eyes for both command execution and feedback observation. Furthermore, the better error score associated with the See-Thru device is promising for its safe deployment in real-life situations as potential drivers are more capable of making fine navigational adjustments to avoid obstacles and hazards along their route.

Although the data for the quantitative measures shows positive results favoring See-Thru, it is essential to also understand the target community's feelings, comments, and critiques. More participants prefer to use the See-Thru prototype over the screen-based state of the art as it affords a more natural and intuitive driving experience, which validates our research hypothesis. Regardless of how fast a task can be completed or how well an obstacle course can be traversed, a good design in this context is one that it is both safe and desirable to use. Conventional screen-based designs meet the basic requirements of functionality for a navigational interface, but they do not sufficiently capture natural human mobile behavior. Rather, the design of these systems still draws from traditional desktop eye-tracking, which pairs directly with computer use by default. This leads to inefficiencies from a usability standpoint when the objective is purely navigational. For instance, P5 mentioned how the video display overly-attracted their visual attention, which made it difficult to successfully plan a path.

Navigating a wheelchair using only eye-movements is complex and dynamic task that requires the user to balance their attention between planning a route in the changing environment before them and engaging with the control interface to send the correct drive commands to the wheelchair. A distracting system thus poses a risk to its operators as they need every bit of focus to avoid crashing. By removing the screen from the conventional equation, the See-Thru interface provides a minimally obstructed FOV that affords a more natural, successful, and potentially safer driving experience. This success highlights the importance of having researchers address the usability preferences of the target audience in their interface designs given the particular context.

It is worth mentioning that although P7 listed a preference for the screen-based interface, their feedback still shows promise for See-Thru. P7 found it problematic that the width of the See-Thru frame still blocked some of their FOV regardless of the design's original intention. However, this device was the very first prototype of its kind, and there is plenty room for improvement to reduce the amount of material needed to fabricate it, such as using a custom PCB with small traces inside the frame rather than jumper cables.

Limitations

The navigation tasks in this study took place in an empty auditorium space with smooth and even floors. It would be beneficial to conduct a more realistic, *'in the wild'* study that reflected the dynamic nature of public environments and uncontrolled spaces. This would shed light on the usefulness of See-Thru in the real world, for everyday use.

Another limitation of this study concerns the phrasing of Question 1, which could introduce a confirmation bias by suggesting that See-Thru should be easy to use. Although the goal of this question was to elicit qualitative detail, most participants simply agreed without elaborating further.

The design of the See-Thru interface does not consider color vision deficiency. While no one in the subject population had symptoms of color-blindness, the See-Thru interface should be updated to accommodate those who do.

Perhaps the biggest limitation to this study was the small number of participants. With only seven recruited wheelchair users coming in for a single session each, the data we collected can only tell us so much about the effectiveness of our interface prototype. While the results do look promising in this preliminary study, it is essential that further studies be conducted to allow for more practice and to yield more statistically concrete findings.

One possible reason as to why volunteer recruitment numbers were low has to do with the stigma within assistive technology that has to do with specialized devices. Embracing a new, specialized technology can be difficult, especially for user's who have grown accustomed to their own unique devices. Considering this, the fact that P2 said they would prefer See-Thru to their existing navigation system after only a few minutes of use underlines the potential that See-Thru has to positively impact its users.

It should be noted that this research is specific to the sole task of navigation, but it is extremely important to recognize that having access to a computer is essential for those living with severe disability. In virtually every case, access to a computing platform allows those living with severe motor disability to communicate and interact with the world around them in ways that our minimally obstructive interface cannot. As such, we recognize that it would not be practical to simply get rid of the user's eye-tracking enabled computer and it would thus be an important task to design an integrated system that incorporates aspects of our minimally obstructive navigation interface with more conventional practices concerning the use of computers.

CONCLUSION

Conventional eye-controlled power wheelchair implementations rely on a digital screen to provide gaze-enabled control buttons and visual feedback to the user. This screen poses a problem, however, as it directly obstructs the user's FOV. This is particularly problematic if the user suffers from a restrictive mobility impairment that may limit their ability to move and see beyond this screen. The research presented in this paper explores a more minimal feedback method in which an array of LEDs is use to deliver pertinent information relevant to the state of the system as it responds to given eye-based input. This assists the user in their interaction with the wheelchair, while simultaneously avoiding the need for a bulky screen that obstructs the user's FOV. To evaluate See-Thru, we had seven wheelchair users complete a series of navigational tasks using both our interface prototype and a screen-based control. Our results show that the See-Thru system we propose is not only the preferred device for the majority of the participants, but it also performs better than, or at least as good as, the screen-based alternative. By removing the use of a screen as an excessive feedback platform and by considering the preferences of the target audience, See-Thru provides users with a more natural, desirable and safe driving experience.

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