Wheelchair Users Navigational Behavior: Insights from Eye Movement Data and Environment Legibility

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Abstract

This study aims to investigate how eye movement data and the legibility of the environment can help us to better understand the navigational behavior of wheelchair users (WCUs) in urban environments. For this purpose and through a field-based exploratory experiment, the legibility of a route was computed and compared with the visual behavior of two participants with different levels of wheelchair-using experience. The preliminary outcomes show the less experienced WCU has looked more intensively for information in the environment, while the more experienced one engaged in a deep cognitive process to maintain his safety. In addition, we have observed a correlation between the level of the legibility of the environment and the fixation duration and the frequency of saccades between fixations, likely leading to intensive cognitive processes in some situations. Based on these results and upcoming complementary experiments, we intend to better adapt the assistive navigation technologies for the mobility needs of WCU.

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1 Introduction

According to the Statistics Canada survey in 2023, 10.6% of Canadians have a mobility disability, which can affect their social participation and quality of life. According to the Disability Creation Process (DCP) model [3], mobility is a life habit that is influenced by

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interactions between personal factors (capabilities, impairments, identity) and environmental factors (social and physical environments). People with mobility disabilities, among which wheelchair users (WCUs), face significant challenges when navigating in urban environments. Hence, WCUs' perception of urban environment complexity may differ from those of the general population. How easily individuals understand the environment has been described by [11] using the "legibility" concept which plays an important role in individuals' navigation in their environments.

Although there has been a significant amount of research on the mobility of WCUs [12], our knowledge of the nature of their interactions with the surrounding environment still remains very limited. Eye-tracking technology offers an interesting possibility to further explore the visual behavior of people during their interactions with the environment [8]. However, the potential of this cutting-edge technology has not been explored for investigating the navigational behavior of WCUs during their mobility in urban environments.

In this paper, we present a field-based exploratory study. As a part of an ongoing navigational experiment, two WCU participants were equipped with eye-tracking glasses and were invited to navigate a route using Google Maps. Our approach is qualitative. Our objective is to answer the following question: What can we learn about the navigational behavior of WCUs by combining their visual behavior with the information on the legibility of the environment? The findings of this study will ultimately help us better understand the information needed to support WCU navigation and will be leveraged to design more adapted navigation aids for these people.

2 Background

The layout of urban environments profoundly influences people's navigational behavior and their interactions with their surrounding environment. Indeed, the legibility of the environment links human perceptions and spatial cognition to the physical environment [9], influencing their navigational behavior and performance. According to [11], legibility pertains to the ease with which urban places can be spatially understood and comprehended to build an accurate mental representation of the environment supporting navigation tasks. Visual access, connectivity level, and complexity of the environment are among the factors that are most often considered in the analyses of the legibility for wayfinding scenarios [10]. Visual access can be computed through isovist which corresponds to the level of visibility of a point in the environment. The connectivity level between spaces can be assessed based on the number of axial connections between spaces. It indicates the level to which humans come together in one place from other connected places. For the environment complexity, Interconnected Density (ICD) is generally used as an indicator. In fact, ICD shows the average level of connectivity for each node across the entire planar network. Given the fact that WCUs have different mobility experiences in their environment because of their personal factors including their personal capabilities and preferences, the legibility of the environment for WCUs can vary from the general population. To consider this, [1] proposed a methodology for estimating the legibility of indoor environments for WCUs by considering the level of accessibility in addition to the aforementioned factors. We will rely on this approach in this study.

In addition to the legibility analysis of the environment, eye movement data serves as a valuable tool for studying people's navigational behavior and their interactions with their surroundings. Indeed, eye-tracking data can reveal information on how people visually explore their environments. Eye movement data can be classified into primary components such as fixations and saccades. Fixations correspond to situations when eyes stay relatively focused spatiotemporally and saccades are the rapid movement of the eyes happening between fixations [8]. Fixations and saccades have various metrics (ex. frequency) that can enable us to better understand human visual behavior, perception, and cognitive activities while executing navigation tasks [5]. High fixation duration may occur because of the attractiveness of features [7] or when a task is difficult and users face a higher cognitive effort [2]. Saccades, on their part, are indicative of search processes. A higher number of saccades indicates a complex searching process or less efficiency in searching [6].

While advances in eye-tracking technology have led to increased research on navigation, human perception, and cognitive processes, WCUs' navigational behaviors have been largely overlooked in these studies. In the following section, we investigate the navigational behavior of WCUs by using eye movement data as well as information on the legibility of the environment.

3 Methodology

3.1 Participants and procedure

As a part of an ongoing research experiment, two participants (men, 40-50 y.o.) were involved in this exploratory study. They rarely performed navigation per day (i.e., less than one time). The first WCU had approximately 1 year of wheelchair-using experience, while the second WCU was more experienced, with 19 years of experience. The recruitment criteria were: being unfamiliar with the study area, being able to independently propel their manual wheelchair for the distance of the route, having at least 1-year experience using a wheelchair and navigational technologies (to ensure data collection validity), and having normal vision. The participants were recruited with the help of relevant organizations, such as the Interdisciplinary Research Center in Rehabilitation and Social Integration (CIRRIS), as well as through social media and the websites of local special interest groups.

For the navigation experiment, a 1-km route was selected for this study, located in the Saint-Roch district in Quebec City (see Figure 1). This district has numerous accessibility challenges for WCUs. The selected route is also composed of a couple of T-intersections, four-way, and five-way intersections as well as various obstacles and barriers (e.g., steep slopes, cracked and uneven sidewalks, and crosswalks without traffic lights). In this route, sidewalks and crosswalks are identified by Si and Ci respectively. In addition, a few stops were considered along the route to allow participants to take a rest.

Figure 1 The sidewalks and crosswalks navigated by the participants.

During the navigation experiment, following initial training, participants were asked to navigate the given route while wearing a Tobii Pro Glasses 3 and receiving route instructions from Google Maps through a cell phone fixed on their thigh. In doing so, their location was recorded by the GPS of the cell phone per second. The participants were accompanied by the researchers to ensure their security and comfort. The participants were also financially compensated for their participation in the experiment.

3.2 Data analysis processes

To assess the legibility of the environment, different factors including visual access, connectivity, complexity, and accessibility of the route were processed. We used the isovist tool of Depthmap software for visual access calculation. The study area was first split into a grid, and then the visual access for each cell was estimated. Places with a high level of visual access are considered to be more legible. Regarding the connectivity level, we used the axial map method. Each axial line was assigned a numerical identifier based on its number of connections with other axial lines. In a graph, the ICD of a vertex can be estimated according to the number of edges that connect to that vertex. Legibility is inversely related to the degree of connectivity and ICD. Also, a personalized accessibility assessment was done for the participants according to a research work presented in [4] where both personal factors, as well as environmental factors, were considered for recommending adapted routes within MobiliSIG assistive navigation tool developed for WCUs. This personalized accessibility assessment resulted in very similar results for both participants.

Then, all the factors were normalized and integrated into the legibility of the route. Since the legibility of the route was similar for both participants, the legibility of the route for the second participant was considered for the following analysis (see Figure 2). The legibility level for some parts of the route, including S12, S18, C5, and C8 was comparatively lower than the rest of the route, while S3, S5, S6, and C1 had relatively higher legibility levels. These parts will be further discussed in the results section.

Figure 2 The environment global legibility.

Analysis of the collected eye movement data from the experiment involved multiple steps. First, fixations (>100 ms) and saccades were computed using iMotion software. Then, this data was annotated according to different parts of the route. We considered five categories (areas of interest (AOI)): Route (sidewalks and crosswalks), Cell Phone (Google Maps), Building, Green Area, and Other Objects (cars, people, etc.). To find the semantics of attention-grabbing features for the WCUs, we mapped the fixation points to their corresponding AOI with a deep learning technique, panoptic image segmentation in the Detectron 2 tool [2].

[2] `https://github.com/facebookresearch/detectron2`

Having computed the legibility of the environment and identifying the fixation points for each component of the route, we then attempted to explore the relationship between these two groups of information. for this purpose, we geolocalized eye movement data and computed fixation and saccade metrics to understand how WCUs interact with their environment while navigating. We present some of our findings in the following section.

4 Results

The total number and duration of saccades and fixations of the participants were computed and illustrated in Table 1. While the saccade count and duration for the first participant with only 1 year of experience as a WCU were higher. The number of fixations and their duration were significantly higher for the second participant with 19 years of experience. According to these data, the first participant has likely engaged in an information-searching process. On the contrary, the second participant was highly fixated on the environmental features along the route to perform deeper information processing.

Table 1 Comparison between fixations and saccades for the participants.

WCU	Navigation duration	Fixation count	Fix. duration	Saccade count	Sac. duration
1	25 min	775	Min:100.1msec Mean:198.1msec Max:1642.9msec	44898	Min:20msec Mean:266.6msec Max:1362.4msec
2	20 min	2202	Min:100.1msec Mean:241.5msec Max:3726.7msec	27019	Min:20msec Mean:208.8msec Max:1122msec

Regarding the geolocalized fixations along the route (see Figure 3), we see that the second participant focused more on the environment than the first one. Besides, Figure 3 compared to Figure 2 shows the relative relation between the legibility of the environment and the distribution patterns of the fixations on specific objects. The parts of the route with lower legibility levels are relatively associated with a higher number of fixations. As we can note in Figure 3, segments such as S18 and C5 got more fixations on the Route.

Figure 3 Mapped fixations on the Route (orange), Cell Phone (red), Building (pink), Green area (green), and Others (grey) for (a) the first participant and (b) second participant.

For a more in-depth analysis of the cognitive activities of the WCUs, we have computed the mean fixation duration (i.e., the ratio of fixation duration on each AOI in each part of the route to the duration of navigating in that part) and the frequency of saccade between fixations according to their semantics for the route's parts for the participants as shown in Figure 4 (a) and (b) and Figure 5 (a) and (b).

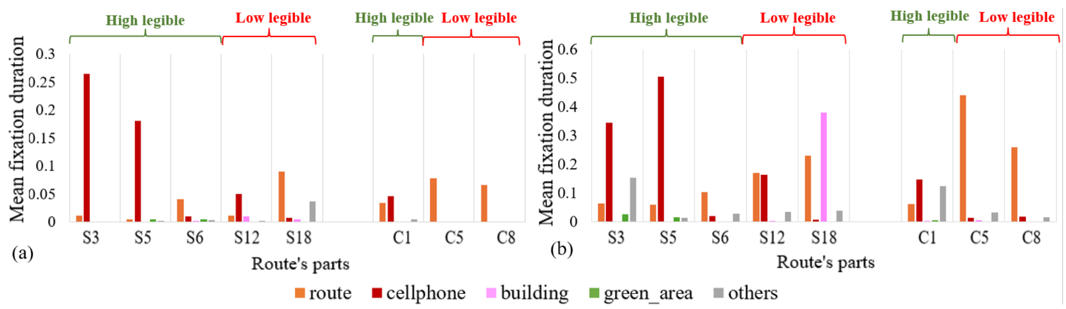

Figure 4 Mean fixation duration on AOI for (a) the first participant, and (b) the second participant.

In the following, the aforementioned metrics and information on the legibility of the environment for each part of the route are used to analyze the participants' navigational behavior according to the AOI categories.

Route category. The low legibility level of route segments mostly due to accessibility challenges might prompt the participants to engage in the considerable fixation duration and frequency of saccades on the Route. This likely led them to perform complex searching processes on the route and experience mental effort to confirm their safety and security. This is evident by the most considerable values allocated to S18 possibly because of slope challenges (see Figures 4 and 5). The narrow and uneven sidewalk of S12 likely caused the considerable mean fixation duration and saccades frequency on the Route for the second participant, while the first one had frequent saccades between the Route and Building as he was not cautious enough about accessibility problems (we helped him on this part). The presence of an upward slope on the following route's part of S5 and S6 led to fixations and saccades on Route, despite their good legibility. A broken curb cut and lack of traffic lights on C5 and C8 also made the participants allocate fixations and saccades to the Route. Notably, they also directed fixations and saccades to the Route at a traffic light on C1.

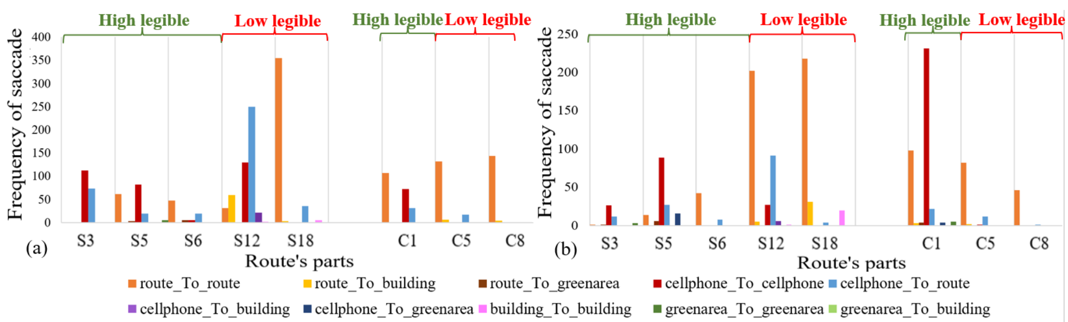

Figure 5 Frequency of saccade between AOI for (a) the first WCU and (b) second WCU.

Cell Phone category. Not only low-legible route segments but also good-legible ones led to the considerable mean fixation duration and saccade frequency on the Cell Phone. Route segments like S12 with poor visual access resulted in a high level of mean fixation duration on the Cell Phone and saccade frequency on the Cell Phone and Route-Cellphone, as well as Cellphone-Building. There was a considerable saccade frequency between the Cell Phone and Route on C5 and S18 as well. In addition, the increased ICD level in certain route segments has prompted the participants to have considerable saccade frequency between the Cell Phone and Route to process information, causing more cognitive effort. Complex route instructions can mitigate this situation, resulting in checking their maps and interpreting the route instructions to find the route. This has occurred at the end of S3 because of the increased route complexity. A similar pattern happened for C1. Additionally, the clearer navigation and good legibility on S3 and S5 might also encourage the participants to allocate high fixation duration and saccade frequency to the Cell Phone rather than the Route. Besides, a high frequency of saccades on the Cell Phone at crosswalks also happened when there was a traffic light (like C1).

Building and Green area. Considerable saccade frequency on the Building was observed at S18 for the second participant, likely for the sake of exploration. Additionally, saccades on the Green Area may be observed for the segments with good legibility like S5.

5 Discussion

In this study, we explored WCUs' interaction with the surrounding environment through the measures of eye movement data and the legibility of the environment. The primary results showed that the more experienced participant in using the wheelchair likely faced a deep cognitive process as he directed more fixations and saccades to the Route and its accessibility challenges compared to the first participant. This behavior likely stems from his higher spatial awareness and ability to tackle diverse obstacles. In contrast, the less experienced participant predominantly explored and searched the environment through saccades.

Additionally, this study highlighted a certain correlation between environmental legibility and eye-tracking metrics. The accessibility challenges that highly impacted the participants' locomotion, may led to high fixation duration and saccade frequency on the Route. The high ICD level in some segments may cause high saccade frequency between the Cell Phone and Route and other AOIs, engaged in performing wayfinding tasks like relating map information to real-world objects for orientation purposes causing significant cognitive effort. In addition, restricted visual access may cause a high fixation duration and saccade frequency on the Cell Phone or between the Cell Phone and other AOI in executing wayfinding tasks. Notably, Google Maps route instructions, in some cases, have caused more confusion and influenced visual behavior and eye movement metrics (ex. increased fixations or saccades). Finally, we could not find any clear relationship between the connectivity factor of the legibility and the visual behavior of WCUs. This might need further investigation with a complementary experiment.

Despite these interesting findings, we are aware of the limitations of this study in the real environment that need further investigation. Notably, dynamic aspects of the environment (e.g., ambient light, different temporary settings) have impacted the visual behavior of our participants while performing their navigation. For further validation, a larger sample of WCUs and additional qualitative information from the users, such as their feedback on encountering obstacles and facilitators along the route, are being considered in our ongoing research. These relevant results will be presented and discussed in our future work.

6 Conclusion

The objective of this study was to investigate how the information from eye movement data and the legibility of the environment can help to better understand the navigational behavior of wheelchair users (WCUs). To this end, a navigation experiment was carried out with the participation of two WCUs equipped with eye-tracking glasses. The participants were asked to navigate along a predefined route using Google Maps instructions. Their eye movement data were assessed with the information on the legibility of each part of the route. According to our preliminary outcomes, parts of the route with low legibility were significantly correlated with changes in eye movement metrics, such as fixations and saccades. This was interpreted as being partly related to the cognitive process engendered by navigation tasks in those specific route parts. Ultimately, the findings of this study will help us better understand the navigational behavior of the WCUs and assist in designing more adapted navigation aids for these people.

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