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Design and Evaluation of an Inclusive Autonomous Vehicle User Interface Developed for Persons with Visual Acuity Loss

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Abstract

This research focuses on evaluating a user interface (UI) for an autonomous vehicle (AV) with the goal to determine the most suitable layout for persons with visual acuity loss. The testing procedure includes a Wizard of Oz AV for simulating an automated ride. Several participants are included in the study and the visual impairments are simulated by specially designed glasses. The conclusions help to determine the optimal graphic design of the UI that can be independently used by persons with blurred vision. The results can be applied to improve the inclusiveness and ergonomics of vehicle UIs.

Keywords: inclusive design, autonomous vehicles, user-centred design, user interface, Wizard of Oz experiment

1. Introduction

Even though the autonomous technology has matured significantly during the years and there have been several successful attempts for launching fully autonomous vehicles (AVs) on the road commercial use of AVs still hasn't happened. According to the Society of Automotive Engineers (SAE International, 2018) autonomous vehicles with highest level of automation (level 5) are vehicles using complete automated driving features that do not require a person to be involved in the role of a driver. Automobile manufacturers invest in research and development to make such self-driving cars a reality in the upcoming years. The reason for this, are the numerous benefits the use of automated systems can bring. Besides increased safety, there are numerous other positive aspects of AVs: they make the transportation safer, they reduce congestion, improve the use of urban infrastructure, optimize fuel savings and, very importantly, offer the opportunity for safe and independent travel to persons with impairments (Union of concerned scientists, 2017; Lewandowski, 2018).

Research on the subject of transportation and persons with disabilities show their dissatisfaction with the current transportation options they have available. Persons with impairments report obstacles with nearly every aspect of the transportation system, they use each mode of transportation less often compared to persons without a disability, and driving a car is not an option of them (Claypool, Bin-Nun, Gerlach, 2017). Moreover, individuals with different types of disabilities express a strong desire to be able to travel independently and show a willingness to possess and use a self-driving car (Allu, Jaiswal, Lin, Malik, Ozay, Prashanth, 2017). These facts mark persons with disabilities as potential early adopters of fully AVs. That is the reason why "disability has been a leitmotif of the discourse of connected cars".

Another important aspect is to understand how the different types and degrees of disabilities are linked to different transportation issues and specific requests the users with impairments may have from an AV. In this sense, the most challenging task is enabling independent travel for the persons with visual impairments. Most information provided to the traveller is in the form of visual cues. Alternative forms of information display are very rare and travellers with visual impairments are at a significant disadvantage with respect to their sighted counterparts (Harper, Green, 2000). The information capacity of vision is higher than of audition since the optic nerve contains over 1 million fibres in comparison with the auditory nerve that has only 30,000 fibres (Kristjansson, et al., 2016). Therefore, when designing the inclusive user interface (UI) of AVs special attention and research is needed to provide equal usability, safe and intuitive vehicle-passenger interaction for persons who have reduced sight (due to different medical conditions, or age).

This paper aims to provide an overview of existing guidelines for designing an inclusive interface for persons with visual impairments, with a focus on visual acuity loss. The recommendations and universal design principles are applied in the development of three wireframe options of a UI intended to be used in a fully autonomous vehicle. The Wizard of Oz experimental procedure is chosen for evaluating the provided wireframe variants and deciding which is the optimal UI layout for individuals with visual acuity loss.

2. Background

This section of the paper includes background information which helped to define the UI design and testing procedure. Visual acuity loss is explained as a medical condition and an analysis of recommendations for inclusive UIs for persons with this eye condition is done in order to draw the most important guidelines that need to be followed in the interface design process.

According to a fact sheet on blindness and visual impairment by the World Health Organization (WHO), at least 2.2 billion people have a near or distance vision impairment (WHO, 2021). As defined by News Medical, different causes result with different manifestations of visual impairment and most common triggers are glaucoma, age-related muscular degeneration, cataract and diabetic retinopathy (Mandal, 2019). The five most common categories of visual impairments that impact the use of screens, as defined by the World Wide Web Consortium (W3C), are: visual acuity (clarity) or vision blur, light sensitivity, contrast sensitivity, field of vision and colour vision (Allan, Kirkpatrick, Lawton Henry, 2016). The mild and severe vision blur results with the broadest range specific UI requirements. The loss of visual acuity (clarity or sharpness of vision) can be in a form of blurred vision that causes loss of focus, or generalized haze with the sensation of a film or glare in the viewing field.

Recommendations for the characteristics of the UI for persons with visual acuity loss are quite specific.

The most common approach is to use multimodality. According to research, the optimal combination for persons with reduced sight is to use visual elements combined with tactile cues and auditory messages (female voice is preferred) (Ferati, Murano, Giannoumis, 2018).

In order for the UI to be simple and easy to understand for persons with reduced sight, researches also propose the minimal use of text, replacing it with graphics for visual information and voice when needed (Nadeem, 2014). The placement of visuals should be in the zones of most comfortable head movement. Researches state that the head moves most comfortably up and down in an angle range of 15 degrees, and angles up to 30 degrees belong in the comfort zone (Bhise, 2012; Tilley, 1993; Macey, Wardle, 2008). Placing touch screens under an angle of up to 30 degrees allows them to be easily located and used with quick eye movements without requiring sharp and drastic head movements.

The content used for the displays should be carefully chosen with appropriate light levels, contrast colours, adequate size, contrast between text and background, with isolated priority information, eliminating unnecessary decorations and clutter (Shaheen, Niemeier, 2001). Darvishy and Hutter in their paper regarding recommendations for avoiding barriers to mobile application usage by the elderly who are dealing with issues like vision loss propose more principles for the used content in UIs (Darvishy, Hutter, 2018). Among them are: consistent layout; elements corresponding with the user's mental models; visible and acoustic feedback; self-explanatory navigation elements; navigation elements accessible at all times (fixed navigation bar); minimal number of navigation elements; short sentences, simple language; active speech (opposed to passive); absolute minimum of 12pt as font size; images relevant to the text; interaction elements displayed in a way that the function of the element and the way that it works are obvious to the user etc.

Other important accessibility basics for UI features regarding the use of colour, contrast, structure and content are provided in various literature sources (Graham, Goncalves, 2017; Fulton, 2017; Hamill, 2018). Useful Detailed guidelines are also provided by the W3C describing the needs of people with low vision for electronic content, tools and technologies (Allan, Kirkpatrick, Lawton Henry, 2016).

These lists consisted of minimum UI design requirements for providing accessibility for persons with visual impairments include: limited colour palettes; elements containing both text and icons to make the goal clear; strong contrast between the text and the background (according to W3C (Allan, Kirkpatrick, Lawton Henry, 2016), at least 4.5:1 should exist between a text and its background, or 3:1 for larger text (24px or 29px bold)); clear structure (one method to grade the visual clarity of a UI is to use a blur test (Hamill, 2018) meaning that when blurred, the structure of the information should still be clear even when the text can't be read); filled icons instead of thin-line icons; icons without borders or shapes surrounding them due to recognizable silhouettes; sufficient white space around click and tap targets; avoided decorative fonts etc.

The choice and application of all these principles in the development of the UI variants is explained in greater detail in the following section of this paper.

3. Methodology

For the goal of this study the Wizard of Oz method was chosen as a low cost and effective option for simulating an automated system. Other researches based on this methodology include using vehicle simulators to examine user needs and behaviour in AVs, as well as ways in which AVs should interact with humans (Detjen, Pfleging, Schneegass, 2020; Ka-Jun Mok, et al., 2015). In this case, a real vehicle was used with a hidden driver in order to simulate a fully autonomous drive. One tablet that contained the developed UI was placed in the back for allowing "vehicle-passenger" interactions. The experiment was conducted based on a pre-determined travel scenario and pre-determined travel route. Visual acuity loss was simulated using specially designed glasses with lenses that blur the vision. Each participant went through the same scenario three times, each time using one of the three different wireframes that were developed. The order of use of the variants was randomized between participants to avoid possible learning effect favouring some of the UI versions. After the experiment, the participants' opinions were collected by conducting questionnaires.

3.1. Developed user scenario

The process began by developing the use-case scenario of the AV and the possible vehicle-passenger interactions that might take place in autonomous driving mode in order to determine the needed content for the UI. The information flow, or vehicle-passenger interaction, in an AV takes place in 5 main activity groups: enter, set up, navigate, get comfortable, be entertained (Lewandowski, 2018). The processes flow from one activity to another with the possibility of this flow being broken by other factors, mostly from the outside environment. Taking this into consideration, use-case scenario needs to be developed and evaluated not excluding some possible interruptions in the activity flow coming from external factors. "Breaking the flow" should be done in order to evaluate if the passenger is able to recognize the urgent and informative messages the vehicle is trying to convey along the journey and respond accordingly. Therefore, for the evaluation stage of the UI, a standardized and comprehensive use-case to be completed by all the participants was defined to make sure that the test procedure generates comprehensive and comparable results (Naujoks, et al., 2019). The developed user scenario is explained in the block diagram shown on (Figure 1).

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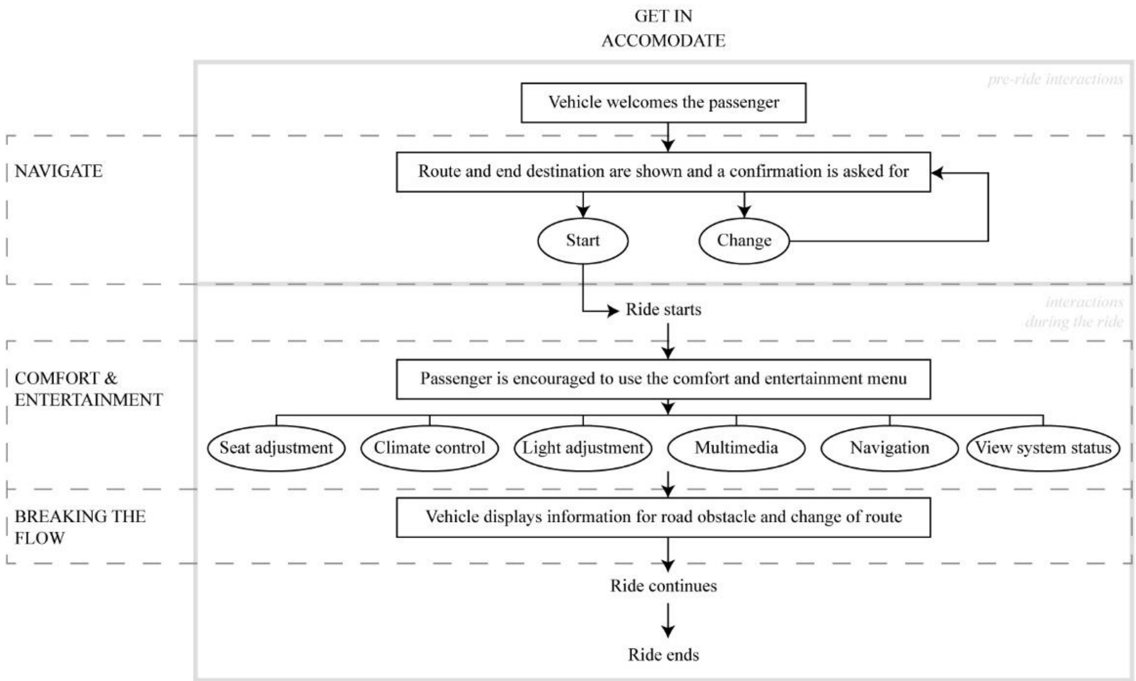

Figure 1. Use-case scenario

3.2. Designed UI graphics and wireframe variants

The use-case scenario was helpful for determining the menu items of the user interface. The goal was to provide the most crucial options avoiding excessive information or clutter that might be confusing for a user with a visual impairment. The final result was a menu containing the following tabs: navigation, seating adjustment, climate control, light adjustment, multimedia and system status.

The interface was designed using the software Adobe XD.

The elaborated inclusive recommendations were applied in the design process. The main criterion for selecting relevant guidelines was following the needs related to visual acuity loss. Users living with this eye condition have specific requirements for perceiving (size), spacing (letter and word spacing, white space, margins) and recognizing elements (different style for differentiation) (Allan, Kirkpatrick, Lawton Henry, 2016).

Sizing of all content during the design of the app variants was carefully chosen. The smallest font size in the interface was 48pt. Most was the text with a size of 72pt. The smallest button size used was 266x131px to provide a large clickable zone.

Margins of up to 100px were used around buttons and text to provide sufficient spacing.

Several methods were used to create easily identifiable elements. The main color combination applied was #2b344a and #b2f1ee which provided a sufficient contrast. Roboto was used as a sans-serif font which to provide high readability. Universal symbols were used and all the icons were filled instead of outlined. All buttons and clickable areas had the familiar button shape of a rectangle with rounded corners and a drop shadow effect. The used colors for buttons were red and green according to the choice the button offered – green for confirmation and red for cancelling or stopping. The grid for the UI was divided in thirds and the content was clearly separated and grouped in order to enable intuitive use. In all three variants the following sections were included: header, menu, map, information, and options of the menu item selected.

In addition, multimodality was offered by using a personal assistant with a female voice.

After selecting these general principles there were several segments remaining which offered the possibility to be experimented with when establishing the differences between the three app wireframe versions. One part of the reviewed literature sources suggested a minimal use of text, replacing it with graphics and photographs. However, another part of the recommendations suggested using images relevant to the text and elements containing text and icons in combination. This was chosen as the first aspect that should be tested by the different app versions.

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Another point chosen for testing was the use of navigation elements that are always visible. This was in contradiction with using a large scale for all available options since a fixed navigation window significantly reduced the remaining screen area available for other features.
One more aspect that needed testing was the optimal positioning of the menu bar. All three developed models needed to offer a menu bar position corresponding to the users' mental models. However, the goal of choosing to provide menu position variations was to decide which position allows maximum usability for persons with a blurred vision, which is an information that wasn't found in analyzed sources.
Similarly, the optimal positioning of the information and notifications section was chosen to be analyzed with the goal to establish the zone that provides best visibility. Successfully conveying important messages vehicle-to-passenger is crucial in automated driving for gaining trust in the system, especially when persons with a visual impairment are included.
Variant no.1 (Figure 2) was designed with header bar and a menu bar with a same height. The menu bar was placed at the bottom of the screen and contained only icons to represent the available options. The left third of the UI grid was used to display information and the central two thirds of the screen were used to display the content of the different menu options. For example, the navigation showed a large map, the seating adjustment showed buttons for choosing a preferred seating position etc. The map was only visible if the person user clicks on navigation. Messages (information and notifications) only appeared as pop-up windows.

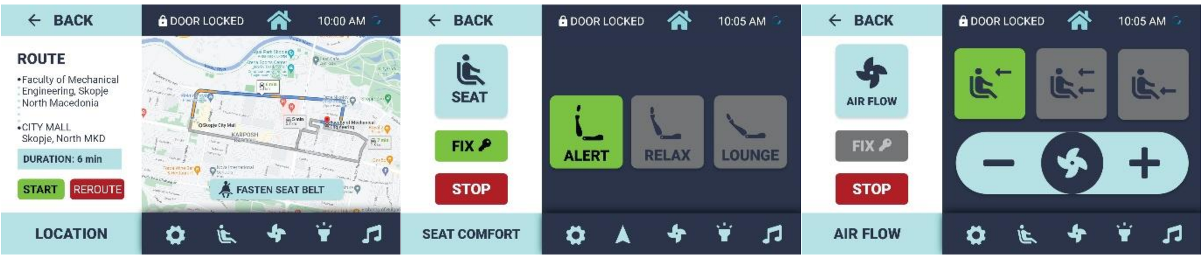

Figure 2. UI wireframe variant no.1

Variant no.2 (Figure 3) was designed with a menu that not only contains icons, but also text in combination. This was done in order to determine if using only icons is not clear enough for persons that have a blurred vision. The left third of the grid in this case contained the menu buttons (icons and text) which left the two thirds at the right of the screen for displaying all other information. As previously explained, since in some of the analysed guidelines it was mentioned to have a constantly available navigation map, this variant had a special corner for displaying the map in all the interface screens. The two-thirds-right-zone was divided in half. The bottom half was also split in two zones – left box displaying the map and right box displaying information and notifications. The top half of this section was used to display the content of different menu options. The position and size of the header was the same as Variant no.1.

Figure 3. UI wireframe variant no.2

Variant no.3 (Figure 4) was more similar to the previous variant with the difference that the menu was placed as a bar on the right of the screen and contained no text, only icons. The left third of the screen was used for a constant display of the map and on top of the map notifications and information appeared. The central zone was used for the content of the menu options. The header was once again same.

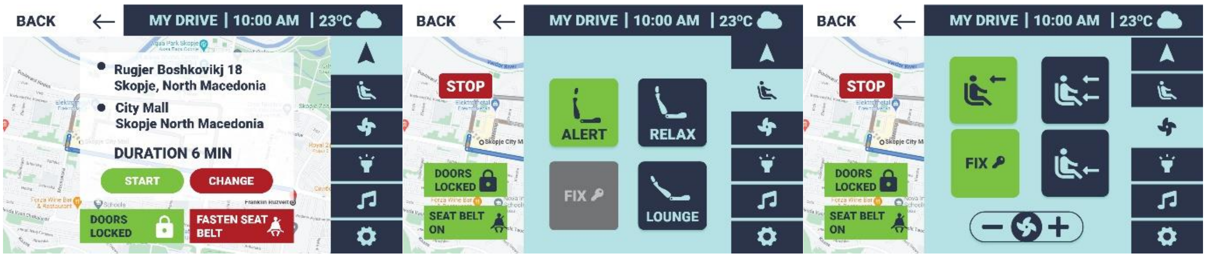

Figure 4. UI wireframe variant no.3

3.3. Gathered participants

In total, 10 participants were recruited for the study from personal networks. The participants were carefully chosen with different backgrounds in order to represent various categories of users. There were 5 male and 5 female respondents, aged from 22 to 58. All of them stated they have a solid familiarity with technological devices. Involving participants with a high understanding of technology was important for eliminating any possible issues with the usability of the app that are not triggered by the simulated vision impairment.

3.4. Used equipment

The vehicle used for the procedure was an Opel Astra J which was slightly modified to represent an AV (Figure 5, left). In order to make it into a Wizard of Oz AV the front part was divided from the back part using a thick cardboard that hid the driver from the participants seated on the back seats. The cardboard was painted black in order to blend in the interior and not attract the attention of the users or distract them from interacting with the interface. A tablet holder was mounted on the headrest of the front seat and the 10-inch tablet displaying the UI was placed on the holder. The glasses for simulating the vision impairment (Figure 5, right) were previously ordered from the University of Cambridge Inclusive Design Toolkit (inclusivedesigntoolkit.com/). The glasses simulate a visual acuity loss, or more precisely, as stated on the Cambridge Inclusive Design Toolkit website, “the effects are representative of an inability to achieve the correct focus, reduced sensitivity of retinal cells, and problems with internal parts of the eye becoming cloudy, effects that typically occur with ageing and the majority of eye conditions, as well as not wearing the most appropriate corrective glasses”.

Figure 5. Used testing equipment, a wizard of oz AV (left) and simulation glasses (right)

3.5. Testing procedure

The study was conducted by scheduling each participant at a different time, with a time gap of 40 minutes between participants. Upon arrival the participants were firstly given the research protocol and instructions in order for them to clearly understand the purpose of the experiment and their role in the procedure. They were explained that they should imagine they are a person with a visual impairment using an AV for shared rides. They were also explained they will be using simulation glasses and will be interacting with three different UI versions inside the vehicle. They were encouraged to explore as many options on the given interface as possible. However, no additional information regarding the menu, content, or messages of the interface was shared with them with the goal to determine if they will be able to understand and use all the content successfully.

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Then, the participants were provided with simulation glasses and they wore 3 pairs of glasses stacked one on top of the other which made their vision about 0.49 logMAR worse (logMAR is the visual acuity score with reference to the logarithm of the minimum angle of resolution (Goodman-Deane, Waller, Collins, Clarkson, 2013)).

Before the three simulation rides, participants were firstly given the chance to interact on the tablet with various UIs not designed to be inclusive, with no high contrast colours, large fonts, or limited information. This was done for the participants to explore the daily used apps with a "vision impairment" and to later on be able to pinpoint the crucial benefits of the specially designed graphics.

As previously mentioned, the experiment was conducted based on a pre-determined travel route. From the starting point, the vehicle drove for about 3km. One ride lasted for about 10 minutes which was sufficient time for the participants to be able to explore the options of the UI (Figure 6). The same ride was repeated three times under the same light conditions. Each time the researchers set up a different UI variant for the participant to use. The total time spent in the vehicle was 30 minutes for each user.

After the experiment, structured and semi-structured questionnaires were given to each participant in order to gather their impressions. They were also encouraged to explain their answers and provide additional comments or ideas. The gathered results are elaborated in the next section.

Figure 6. Users interacting with the developed UI

3.6. Results and discussion

The initial results showed that all three UI wireframe variants were successful. Participants found the inclusive versions more usable in comparison to using a regular interface. The answers to the last two questions "What was your general impression of this UI variant?" and "Did you feel safe and confident during the use of the UI despite your blurred vision?" were answered positively by all participants for all the three versions. The answers were that the layout was more or less clear and the majority of buttons and icons were easily recognizable.

However, the answers to the first part of the questionnaire, where the respondents were asked to use a Likert scale to grade the usability of all three UI variants, showed the preferred wireframe was Variant no.1. This result is visible on the bar chart given below (Figure 7). By looking at the results on the bar charts we can see the uncertainty bars are small illustrating that all the answers were similar to the mean without large value variations. This is a result of similar impressions among the respondents when interacting with the app variants. For some of the questions we notice an overlap in the uncertainty bars indicating that these results are not statistically significant. This is mainly regarding the positions of buttons and tap areas and the identification of symbols and proves that the application of principles for perceiving, spacing and identifying elements was successful in the three offered app versions. However, the answers to the other questions reveal less or no overlap in the uncertainty bars meaning that those results are likely to be statistically significant and further testing should be done. This is regarding the

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overall usability, the structure of the app and the confidence while operating. The difference is mostly evident when the first and third version are compared. This indicates that the layout of the first app version is most easy and intuitive to use.

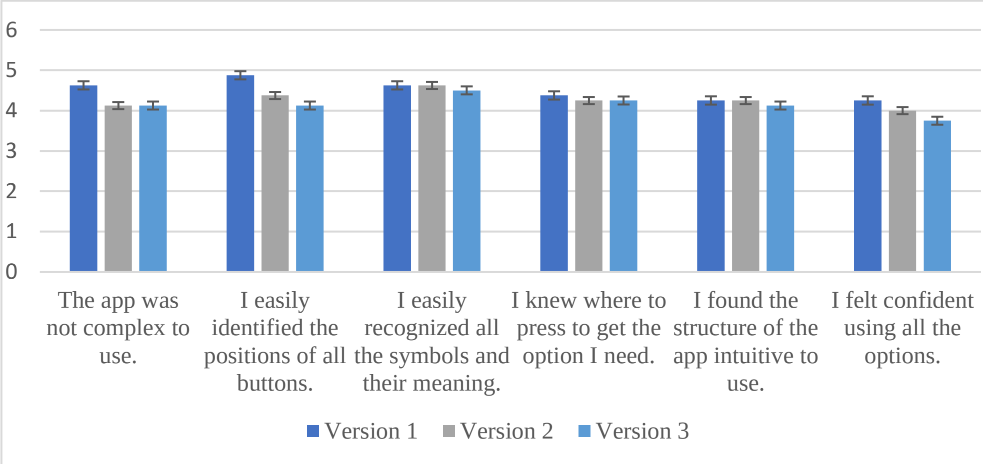

Figure 7. General rating of the three versions of the UI

The responses to the open type questions revealed to a further extend the reasons for the results collected from the Likert scale questions. The answers indicated that the second variant appeared most intuitive at first sight. This was noted by 6 participants. However, during the ride that impression changed and those participants added that several elements during the use created a minor frustration when compared with Variant no.1. Nearly all participants (9) responded that the map in Variant no.2 was too small and unnecessarily took up screen space since it was imperceptible and made some of the other buttons and text smaller as well. For example, when choosing the option to learn more about nearby amenities, the information text was unreadable. This was commented by 5 of the participants. Another element 6 of the participants pinpointed as "taking unnecessary screen space" was the text in the menu. In addition, the position of the bottom right corner for displaying notifications seemed unnatural to 8 of the participants. Their preferred way for displaying information was through a central pop-up window as included in Variant no.1. Variant no. 3 received similar feedback as Variant no. 2, but all in all, it was perceived as the least useful. All of the respondents answered that Variant no.3 is most confusing, 7 respondents disliked the position of the menu bar, 8 participants disliked the notifications section placed over the map and again nearly all of them thought the map was too small and unnecessary since it reduced the screen space for other content. Moreover, in both Variant no.2 and Variant no.3 most of the participants had difficulties while trying to use the buttons for increasing/decreasing the ventilation intensity and the buttons for previous/play/pause/next of the multimedia menu. These buttons were not large enough. Variant Version no.1 was the favourite because the respondents thought (1) it had the best position for the menu; (2) the most important information was always positioned centrally; and (3) the buttons and text were largest and easiest to recognize and click on. It is also important to note that one thing liked by all participants in all variants were the pre-determined choice options since they were easy to see, understand and use by minimal number of interactions. The majority of answers on the question "What was the easiest thing to use?" were related with the pre-determined choice options such as choosing seat positions or light modes.

4. Discussion

Overall, the design of the UI received positive feedback. Following the guidelines resulted with an inclusive interface which to a great extend can be used by persons with reduced sight.

Based on the chosen Variant no.1 as the most intuitive, useable and inclusive wireframe option additional recommendations for designing a UI for persons with reduced sight can be pinpointed: (1) the most important content should always be positioned centrally on the screen; (2) the navigation map does not need to be constantly displayed on the screen in order to liberate space for larger buttons and

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text; (3) text does not need to be included in the menu bar provided that all icons used to describe the menu options are: universal, filled, with a colour allowing a high AAA contrast between them and the background, and with a sufficiently large size (Variant no.1 had a menu icon size of 90x90px); pre-determined choice options are beneficial for persons who have a reduced sight (the designed UI had such options for the comfort settings provided as choice buttons and these were graded as most simple to use by the respondents); dividing the screen into more than 3 sections is confusing and unnecessary (Variant no.1 had a header, menu bar and options section which proved to be the most intuitive for use while Variant no.2 and no.3 had a header, menu bar, map, notifications and options section which proved to be unclear and more difficult to use for persons with a blurred vision).

While significant efforts have been placed for conducting the study and it proved to be successful for gathering beneficial feedback, there are some limitations that need to be mentioned.

The Wizard of Oz study simulates an autonomous ride. However, the ride in an actual self-driving car would be a different experience due to the exclusion of a driver and the appearance of the vehicle cabin. In our experiment the driver was hidden, but the participants were still aware of his presence which might interfere with the perceived feeling of safety. Moreover, the vision impairment was simulated through glasses. These glasses help to empathize with persons who have a visual acuity loss, but cannot convey what is really like to have an actual impairment. Another point is that the number of involved participants was limited as a result of the current situation with Covid-19 which makes it more difficult to gather participants for an ethnographic study.

Because of these limitations, there is a possibility for further research on this subject. What should be done in the following phase is to optimize the UI based on the results from this evaluation and a conduct a new study with a larger number of participants which have an actual eye condition. The new study can be conducted using a larger vehicle and larger tablet in order to simulate a ride in an AV more accurately.

5. Conclusion

In this paper, a conducted study in which participants with simulated visual acuity loss rode in a Wizard of Oz AV and interacted with a developed inclusive UI is presented. The vision impairment was simulated using simulation glasses. Each participant went through a driving scenario interacting with different wireframe variants of the proposed UI. The study was done with the goal to understand the needs of persons with visual impairments in automated driving, determine the optimal wireframe of the AV interface and expand prior research on developing inclusive interfaces for self-driving cars. With this human-in-the-loop simulation important insights regarding the use of interfaces by persons with a visual impairment were found. In summary, it was found that the participants preferred: a smaller number of sections on the screen; icons instead of text; central positioning of the interactive buttons and most important information; hidden navigation window; pre-determined adjustment choices.

It is hoped that the results from this study will help to improve the understanding of the design requirements for developing inclusive interfaces for persons with visual acuity loss. It is important to note that these conclusions are dependent on the specific type of visual impairment since the research was focused on the particular needs of users with a blurred vision. Other eye conditions might require a slightly different design approach. However, these findings are not only applicable in the design of apps for AVs, but also for standard vehicle models or interfaces with a completely different purpose.

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