Evaluation of Common External Communication Concepts of Automated Vehicles for People With Intellectual Disabilities

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With the future availability of highly automated vehicles (AVs), vulnerable road users (VRUs) will encounter vehicles without human operators. To compensate for the lack of eye contact, realizing communication via external human-machine interfaces (eHMIs) is planned. The adequacy of this regarding people with intellectual disabilities (IDs) is, however, still unknown. This work compares eHMI concepts by their perceived user experience (UX) for people with and without ID to evaluate the inclusiveness of current eHMI concepts. We analyzed related work and derived two representative concepts for a visual and an auditory eHMI. Subsequently, a survey of $N = 120$ participants (64 with, 56 without ID) was performed, comparing the perceived UX of the selected eHMI concepts for visual, auditory, and combined modalities, and a baseline without eHMI using videos of simulations. We then had them assessed using the modified user experience questionnaire - short (UEQ-S). We found that auditory eHMIs performed worse than visual or multi-modal ones, and multi-modal concepts performed worse for people with ID in terms of pragmatic quality and crossing decisions. Our insights can be taken by both industry and academia, to make AVs more inclusive.

CCS Concepts: • **Human-centered computing** → **Empirical studies in accessibility**; **Empirical studies in HCI**; *User studies*; • **Social and professional topics** → *People with disabilities.*

Additional Key Words and Phrases: accessibility, learning disorder, eHMI, automated vehicles, vulnerable road-users

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1 INTRODUCTION

Humans tend to classify humans based on race, language, abilities, or others [90]. The differences in abilities are used to determine special needs for support of various kinds. While helpful for providing support, the stigma of disability promotes the exclusion of people with disabilities [53]. Although up to 15% of people worldwide are legally considered as *severely disabled* [98, 105], they are not equally visible in society, nor equally represented in research [55]. With humans in shared traffic

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spaces being more exposed to harm than people in the passenger compartments of vehicles, they are referred to as vulnerable road users (VRUs) [49]. Further restrictions in perception or mobility can aggravate the problems of VRUs [23]. This problem must be addressed in the development of future traffic. While more than 13% of severely handicapped people in Germany suffer from intellectual disability (ID) or mental impairments and 9% from general cerebral disorders [55], questionnaires of different kinds are primarily designed focusing on people with average abilities [45]. Although IDs have very different phenotypes, e.g., learning disabilities [58], intelligence-reducing conditions [25], developmental disorders [10], or others [77], people with ID commonly have less available working memory (WM) capacity [72, 95].

One of the current research fields for human factors in automated traffic is the communication of vehicles with other road users. Given the lack of eye contact with drivers, communication of intentions has to be technically substituted. One concept for conveying information unidirectionally from vehicles to their environment is external human-machine interfaces (eHMIs). Research in this field is mostly targeted on signaling from vehicles to VRUs [17, 27]. Literature shows that some groups like elderly people are included in research far more than people with disabilities [49]. Only a few publications on people with reduced mobility (e.g., wheelchair users) [5] or visually impaired people (VIP) [20] could be found. Despite the prevalence of people with ID, no work has evaluated eHMI concepts for their special needs. To include this group of traffic participants, the development and design of eHMI concepts need to be more inclusive [93]. With many concepts in exploration and evaluation lacking focus on people with ID, our research questions (RQs) are:

- RQ1: How do people with ID perceive eHMI concepts in terms of user experience (UX) and how would it affect their crossing decision?
- RQ2: Does the perceived UX of eHMI concepts and their crossing decision differ between people with and without ID?

Therefore, we elaborated cross-sectional concepts from published eHMIs and had them assessed through an online survey completed by 64 people with ID and a control group of 56 people without. The assessment consisted of a questionnaire to rate the perceived UX and the individual crossing decision for each presented concept. Institutions for assisted working organized proxy interviews to simplify the inclusion of people with ID. The results of the survey ($N = 120$) show that only auditory single-modality eHMI concepts do not improve the UX, and the ratings are not converging with the crossing decision. We were able to verify that there are no significant deviations between the ratings from people with and without ID.

Contribution Statement: (1): Exploration and presentation of concepts for representative eHMIs with auditory and visual modalities with a special focus on cognitive disability. We presented a green illumination area on the front of the vehicle as visual, and an abstract, slow pulsing sound as an auditory modality. In addition to the single-modality concepts, we provided a concept with combined modalities and a baseline without eHMI. (2): Findings of an online questionnaire ($N = 120$; 64 with a cognitive disability) based on a 3-dimensional (3D) simulation of a virtual encounter of an AV, while objectively assessing the perceived UX and safety of crossing, show that the perceived UX differs in terms of pragmatic quality for people with ID. (3): This shows first evidence for the need for separate assessment of the accessibility of multi-modal eHMI concepts.

2 RELATED WORK

This work builds on research on communication of AVs with VRU focusing on interactions with people with special needs and how to include them into eHMI design and research in general.

2.1 External Communication of Automated Vehicles

Communication with AVs can be categorized from different perspectives. Data-based communication with the vehicle [7] (vehicle-to-vehicle or vehicle-to-everything) requires technical interfaces for interaction. For communication between vehicles and humans, interfaces need to apply to the human sensory equipment [76] or require the human to wear technical devices for communication with AVs. Human-centered interfaces from vehicle to human are considered as eHMI. While most eHMIs concepts target unidirectional communication from vehicle to pedestrians, some work on bidirectional communication has been published [15, 33, 106]. Our work will focus on the human reception part of communication unidirectionally. Most eHMI concepts focus on visual and auditory modalities, but many other modalities (e.g., coding by haptics or body language) have already been considered [27]. Most publications are able to verify the benefits of eHMIs in terms of perceived security [79], but the benefit of specific concepts highly depends on the context of the encounter with the AV, like a pedestrian waiting to cross the street [70]. Another considerable limitation is overtrust in eHMIs, which may cause harm in case of malfunction [50]. Additionally, there are those who doubt the usefulness of eHMIs at all [66]. While visual eHMIs are not beneficial for people with visual impairments [16], both auditory and visual modalities are susceptible to people with ID [81]. We focused on these modalities when selecting representative concepts for our survey (see Section 3.1), as these stimuli are already perceived by people with ID and additional modalities could lead to cognitive overload (see also sensory overload [83]). In the chosen setup, including further modalities was not feasible.

2.2 Interaction with Vulnerable Road Users with Disabilities

Holländer, Colley, et al. [49] defined the group of *especially vulnerable road users (EVRU)* to include groups that do not match the basic characteristics of the default study participants. Those can be defined by age (children or elderly) or specific impairment. While there is some work including elderly people (e.g., [89, 107]), these publications focus on the reduced mobility aspect rather than on the total condition including slower cognitive processes and reduced sensing. There is some recent research on EVRU in the context of public transport [73] or smart cities [82].

Focusing on eHMI specifically, as only a few publications address the inclusion of EVRU, there are some publications that consider people with reduced mobility [5] and VIP [19, 20]. All of these papers concluded that inclusion in eHMI designs benefits from including people with special needs into the design process from the beginning (see subsection 2.3). Shared spaces can cause major distraction [96], causing people with ID to feel unsafe in streets without assistance [30]. While some work focuses on people with ID in a wider traffic context, e.g., integration of perceptual modality principles [24] or assistive devices for cyclists with ID [26], to the best of our knowledge, no experimental research has explicitly conducted a user survey on the communication between AVs and people with ID.

2.3 Designing for People With Disabilities

There are different approaches to creating more accessible designs [74]. There are, however, two approaches that will be particularly highlighted, namely *ability-based* design and universal design, both of which employ completely opposing methods. To enable the creation of systems that are not only applicable to the average person, *ability-based* design [104] suggests focusing on the development of systems that adapt to the individual's abilities instead of their disabilities [14]. VIP, for example, should be enabled to use a system through auditory modalities only. For people with ID, there should be an option to reduce the cognitive complexity of the system. The *universal design* approach is to design systems so that they meet the requirements of every user by default to the maximum possible extent [91]; therefore, adapting to the individual user's abilities is not necessary. Both concepts seem to be adequate to include people with ID in creating surveys or eHMI concepts for the larger population. However, in terms of eHMI designs, it must be kept in mind that systems implementing unidirectional concepts have no knowledge about the receiver and thus cannot adapt to possibly necessary changes of modality. Therefore, developing eHMI with universal design is the more promising approach [57].

2.4 Surveys for People with Intellectual Disabilities

The cognition process of people with ID differs substantially from other people. As a result, the design of questionnaires and used scales must be adapted to be accessible to them. Thus, the questionnaire must use techniques that allow for the substitution of semantic processing in cognition by passive ones, i.e., triggering emotions [97, 100]. Questionnaires specifically targeting people with ID have not been developed to the best of our knowledge and based on statements from professionals. However, there has been a pilot study [43] for an inclusive perennial study conducted by *infas* Institute and the German *Federal Ministry of Labour and Social Affairs* [44, 86, 94] from 2017 to 2021 with the goal of obtaining reliable results in the life context and participation of people with special needs "in allen wichtigen Lebensbereichen" [in all important areas of life] [43, p. 94]. It suggests using a survey where an assisting person is available if support is needed to answer the questions. The level of support is flexible up to the extent that the assistant can serve as a proxy interviewer.

3 REQUIREMENT ANALYSIS AND CONCEPT DEVELOPMENT

3.1 Groups of Vulnerable Road Users and Selection of Representative eHMIs

Holländer, Colley et al. [49] presented a literature survey on the usage of the term "VRU" and counted different types of considered disabilities in papers on VRUs. In the survey, only 6 out of 58 papers (10.34%) used the term VRU in connection to some kind of disability.

For our study, we chose an eHMI matching the most used concepts of the in-depth evaluation by Dey et al. [27], presenting a taxonomy of eHMI concepts published up to June 2019. We compared concepts of eHMIs analyzing the survey paper of Dey et al. [27] to find cross-sections of properties. We selected the most common properties to derive representative concepts for prominent modalities. Our analysis suggests creating a display with **abstract** light signaling **without symbols** displaying **yielding** intention as a **single** state on the **front** of a **car**. We decided to focus on modalities that do not require the human actor to carry any additional device; thus, tactile eHMIs have been dismissed. For alternative modalities, e.g., olfactory or gustatory interfaces, no technically feasible solution has yet been presented.

However, in terms of color, we deviated from white as the color most commonly used [27], as white-colored eHMIs are mainly used with symbols [13, 88, 92] or for projection displays [65]. In direct comparison with other colors, white is perceived as less urgent than others [56], while green is rated best in a yielding scenario [28]. Signaling colors, including green, should be used with caution; therefore, previous work suggests using green only for signaling crossing permission to VRUs [8]. As a result, we considered **green** as representative signaling color. Placing the illuminated area on the hood of the car, a clear position for visual eHMIs, is consistent with the findings of Eisma et al. [31].

For auditory eHMI signaling concepts, fewer publications exist, with most covering an abstract approach [41, 99, 101]. We omitted approaches of spoken text [51, 61, 63, 78], as these exclude people with auditory recognition disorders or people incapable of understanding the emitted language (e.g., also non-native speakers and neurodivergent people). Some approaches used other sounds like music [36] or unspecified abstract sounds [62, 78]. We wanted to present a solution solely relying on emanation from the vehicle (see the design space on eHMI by Colley and Rukzio [18] with the dimension *Locus*), instead of requiring additional portable or wearable devices. To achieve this, we used an **abstract** "electronic" sound pulsing with 1 Hz that is **audible in noisy traffic environments** and expresses danger or generates **caution**. The audio message was intended for pedestrians near the vehicle front by emitting the sound from the **front** in the **driving direction** towards the recipient.

4 SURVEY CONSTRUCTION & EXECUTION

To prevent any COVID-19-related problems during the field phase of our survey, we created videos of 3D visualisations of our concepts.

4.1 Simulation Videos

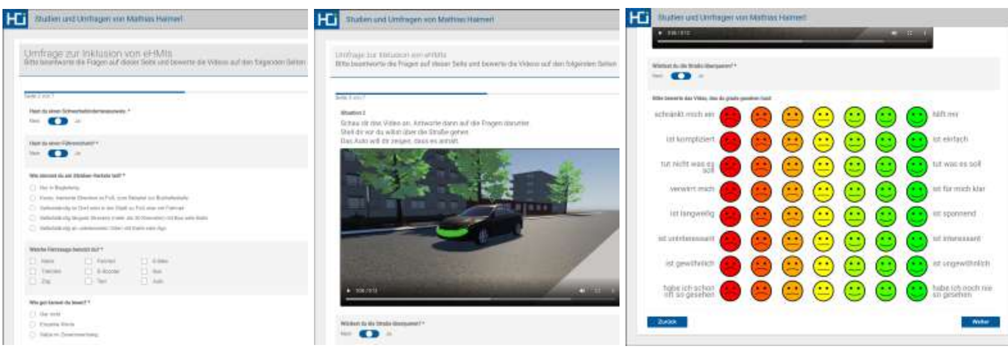
(a) No visual eHMI (b) Visual eHMI

Fig. 1. Screenshots from the videos of the eHMI examples at the end of yielding. The simulated car in Figure 1a has no visual eHMI, while in Figure 1b it is equipped with a partially light-emitting hood that is currently showing the color green. No passenger is present, as this can additionally cause confusion [22]. (Source: own work)

To present the selected eHMI concepts immersively, a 3D simulation was created with *Unity* 2020.3.18f1 using the High-Definition Render Pipeline (HDRP) for realistic rendering results. Using this setup, a scene was created in which a first-person camera follows a car driving down an alley. The assets used were acquired from the *Unity Asset Store* [1, 68, 71]. To further simplify the task to "cross the road", the abstract target was objectified by placing a bus shelter representing the destination on the targeted side of the road. The car was configured to drive at a low speed of around $50\,\mathrm{km\,h^{-1}}$ towards the camera and start yielding when it reached a distance of around 20 m from the camera. As an auditory modality, a sound-emitting eHMI was used with parameters determined in Section 3.1; as visual modality, a green illuminated area was used on the front bumper. For better immersion, the car's engine sound also was altered to express a slowdown. For the four different eHMI concepts, the same scene was reused with modified parameters (no eHMI active, only visual eHMI active, only auditory eHMI active, and both eHMIs active). For each of the concepts, a screen record of the approaching car scene was created and converted to MP4 format with H.264 codec for browser and system compatibility. Each of the videos had a duration of 12 seconds.

4.2 Survey Design

For conducting interviews remotely due to the COVID-19 situation and also for interviewing in parallel in different facilities, a web-based survey was created. As there was no support for external custom form elements at creation time in any major survey tool, we created our own based on *Angular* 9.0.7, using *SurveyJS* 1.8.26 to render the questionnaire. The website was made usable with computers and tablets, as one of the participating facilities works with tablets only. The *SurveyJS* default theme was used, adjusted to the design guidelines of the *Technische Hochschule Ingolstadt*, and the font size was altered to comply with the Web Content Accessibility Guidelines (WCAG) [12]. It consisted of six parts: (1) an introductory video to explain the process; (2) demographic questions



(a) Demographic Questions. (b) Visual modality. (c) Lower part of visual modality.

Fig. 2. Display of different pages of the online survey. (Source: own work)

about the participant; and, (3-6) a video of a situation with no/visual/auditory/combined eHMI, as well as a question on the crossing-decision and an adjusted UEQ-S, described later. After each video, the interviewee was asked to fill in a modified questionnaire on the likelihood of street crossing, followed by a subsequently described, modified version of the user experience questionnaire, to rate the UX of the presented eHMIs [47]. The final page offers a free text input as a feedback field, where optional comments or feedback can be provided. For people participating with assistance, interviewers were asked to transcribe further feedback.

4.3 Interview Methodology and Recruiting

In German disability policy, people who cannot join the so-called *first-labor market* are eligible for employment at workshops for people with disabilities (§§ Kap. 6 SGB XII; 41 Teil 1 Kap. 5, 136-137 Teil 2 Kap 12 SGB IX; WVO). By law, each person engaged in a supportive job is assigned a *labor attendant* who is responsible for this person's professional development to the extent of their capabilities. In accordance with the suggested methodology by Harand and Kersting [43] for interviews for people with ID, a computer-aided personal interview (CAPI) approach was performed, led by their labor attendants, with multiple levels of possible assistance on request. No monetary funding was available for the survey, so no financial compensation was offered to the participants. Nevertheless, the social nature of the study background motivated many participants. Recruiting participants with ID turned out to be complex, so a social working facility was engaged to create a concept to select, contact, motivate, and interview people with ID. Due to the diverse nature of disabilities accounted for in the field of ID [52, 75], a selection of people capable of understanding what they are expected to do and a basic understanding of the rating concept was necessary. This assessment could be performed better through protected working facilities, where most people with mild to medium ID are employed [64]; therefore, we chose to contact those facilities for support. We focused on nearby workshops for handicapped at a distance of max.

100km, limiting the needed travel time for in-person consultations. One of the larger organizations within this criterion is the *Lebenshilfe e.V.* with 17 facilities within our range. We contacted them by email, and non-respondents again via phone call. We were able to get contact people from 9 facilities, from which 6 agreed to participate. The survey administration was explained, either in person or via videoconferencing. Of the facilities, 3 asked for initial support from the authors for the first round of interviews, which was provided, and 3 executed the interviews without further consultation needed.

The acquisition of the control group was performed by asking the facilities' employed caregivers to spread the word, as well as with multiple posts on *Facebook*. We did not employ mailing lists through our academic institution to avoid an over-representation of academics in our control group.

Institutional Review Board Statement: Participation was in accordance with the ethical guidelines stated in the Declaration of Helsinki [6]: participation was voluntary; participants were obliged to provide their written informed consent and had the opportunity to abort the study at any time and leave comments or feedback.

Study participants were not exposed to any kind of physical or psychological harm during the study,which was overseen by caregivers; therefore, based on our university's regulations, ethical approval was not required.

4.4 Measurements

After each condition, participants filled out a questionnaire. As the user experience questionnaire - short (UEQ-S) is a brief questionnaire providing reliable insights into the perceived UX, it was chosen as a basis for measurements [84]. The brevity of the questionnaire requires little processing time, helping people with ID to stay focused. Furthermore, it is flexible enough for modifications while maintaining validity [85]. The UEQ-S consists of 8 semantic differentials, with each item rated on a scale from 1 to 7. As the standard UEQ-S is not easily understandable for all people [48], we employed the adjusted version by Haimerl and Riener [42]. To support people with ID, we connected the lower extreme with negative and the upper extreme with positive emotions. The item scales were represented by smileys ranging from red-colored *unhappy/unsatisfied* to a yellow *neutral* to a green *happy/satisfied* facial expression. As UX is a highly psychological indicator [69], using smileys instead of radio buttons supports emotional binding to the selection, thus supporting affective decisions [3]. Clicking or tapping highlights the respective face. The questionnaire was placed below every video, introduced by a question to rate the system ("Please rate the video you just saw"). Participants were also asked to indicate whether they would have crossed the street ("Would you cross the street?": yes/no).

4.5 Survey Procedure

To establish a personal connection to the participant, a video of one of the authors was displayed on the first page, who introduced the setting as shown in Appendix A. The text was designed to be as simple, personal, and intuitively understandable as possible, making further explanations obsolete. They then signed informed consent and our data privacy statement. On the next page, demographic data regarding age, gender, reading, and writing capabilities, as well as used vehicles and traffic participation habits, were asked. After that, the four conditions were presented on individual pages, ordered by a balanced Latin square. Each one was introduced as "Watch the video. Then answer the questions below. Imagine you want to cross the street. The car wants to show you that it will yield." After each trial, participants answered the questionnaires described in Section 4.4. The last page presented a text input field for free feedback. The study was conducted in German and took approximately 10 minutes per person; in some cases, when participants required more support, it took up to 20 minutes. Where computer-aided personal interviews (CAPIs) were conducted, the local hygiene regulations regarding COVID-19 (ventilation, disinfection, wearing masks) of the individual facilities were applied.

5 RESULTS

As we handled non-normally distributed data, we used the factorial non-parametric analysis of variance (NPAV) provided by Lüpsen [59] and included a random intercept for participants for each dependent variable because of the hierarchical data (measurements nested within participants). For post-hoc tests, Bonferroni correction was used. We used Version 4.1.2 of R and RStudio Version 2021.09.0 with all packages up-to-date as of January 2022.

5.1 Participants

We conducted an a-priori power analysis using G*Power 3.1.9.7 [35]. To achieve a power of .95 with an alpha level of .05, 98 participants should result in a low to medium effect size (0.15 [38]) in a within-between-factors repeated-measures ANOVA with four measurements.

Therefore, in total, we recruited 120 participants (64 with a cognitive disability). Due to technical problems during data acquisition, data regarding the age, gender, and reading and writing capabilities of 38 participants were lost. Therefore, the following description of the participants is based on 82 participants. We recruited 16 females and 22 males (0 non-binary) participants with a cognitive disability and 21 female and 23 male (0 non-binary) participants without a cognitive disability. We performed a chi-square test of independence to examine the relationship between gender and cognitive ability. The relation between these variables was not significant (χ^2(1, N = 82) = 0.08, p=0.77). Participants with a cognitive disability were, on average, M=35.90 (SD=12.80); participants without a cognitive disability were, on average, M=32.20 (SD=10.60) years old. A Mann-Whitney U test found no significant difference between the age of participants for cognitive disability (W = 717.5, p=0.27).

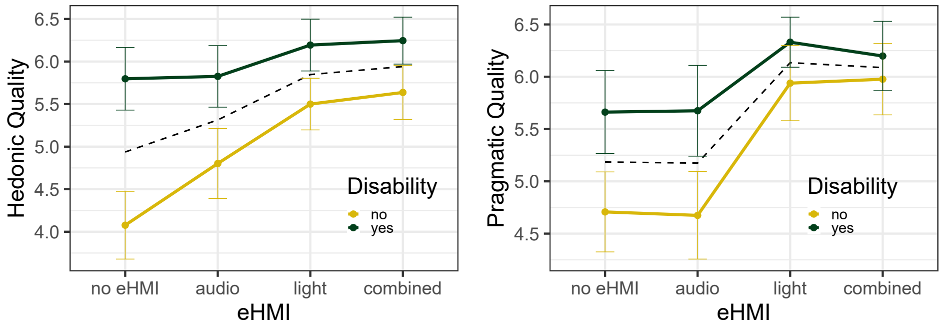
Regarding their ability to read, two participants of the group with cognitive disabilities reported *not being able to read*, 12 reported being able to read *single words*, and 29 reported being able to read *sentences in conjunction*.

Regarding their ability to write, two participants of the group with cognitive disabilities reported *not being able to write*, 11 reported being able to write *single words*, and 30 reported being able to write *sentences in conjunction*.

With regards to their behavior in traffic, one participant stated to only move *with company*, three reported to do *short, trained routes*, fourteen reported making journeys *independently in the village or the city on foot or by bicycle*, 13 reported to *independently travel longer distances (more than 30 km) by bus or train*, and seven reported to make journeys *independently in unknown places with a map or app*. Due to not answering questions, we had to eliminate a further 14 data sets (11 of participants with a cognitive disability).

5.2 Communication Quality

The NPAV found a significant main effect of *cognitive disability* on hedonic quality ($F(1, 104) = 30.16$, p<0.001). The NPAV found a significant main effect of *eHMI* on hedonic quality ($F(3, 312) = 30.80$, p<0.001). The NPAV found a significant interaction effect of *eHMI* × *cognitive disability* on hedonic quality ($F(3, 312) = 6.70$, p<0.001; see Figure 3a). While all eHMI concepts were rated higher in terms of hedonic quality by participants with a cognitive disability, the difference was highest for the *no eHMI* condition. Figure 3a shows that between the *audio* and *no eHMI*, there is almost no difference in terms of hedonic quality. For both, participants with and without a cognitive disability, the *combined* eHMI was rated best, followed closely by the *light*.



(a) IE of *eHMI* × *cognitive disability* on hedonic quality.

(b) IE of *eHMI* × *cognitive disability* on pragmatic quality.

Fig. 3. Interaction effects (IE) on communication quality.

The NPAV found a significant main effect of *cognitive disability* on pragmatic quality ($F(1, 104)$ = 11.72, p<0.001). The NPAV found a significant main effect of *eHMI* on pragmatic quality ($F(3, 312)$ = 32.08, p<0.001). The NPAV found a significant interaction effect of *eHMI* × *cognitive disability* on pragmatic quality ($F(3, 312)$ = 5.52, p=0.001; see Figure 3b). While the ratings in terms of pragmatic quality follow approximately the same trend (no eHMI and audio worst), participants with a cognitive disability rated the *light* eHMI (M=6.33, SD=0.87) higher than the *combined* eHMI (M=6.20, SD=1.20). This was the opposite for the participants without a cognitive disability, who rated the *combined* eHMI (M=5.98, SD=1.24) slightly higher than the *light* (M=5.94, SD=1.30).

5.3 Crossing Decision

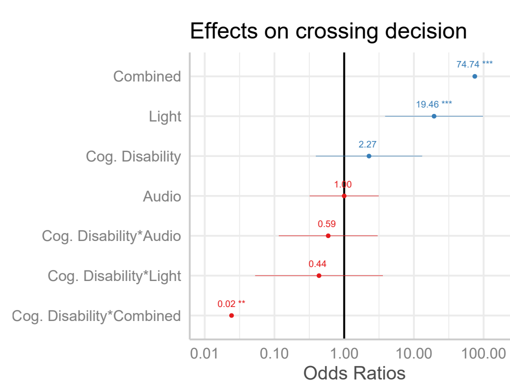


Fig. 4. Fitted logistic model of the decision to cross the road. The Odds Ratios define the probability for a participant to cross relative to the reference category (no eHMI and no cognitive disability).

As the decision to cross (i.e., *Would Cross*) was determined via a boolean value, we fitted a logistic mixed model (estimated using ML and BOBYQA optimizer) to predict *Would Cross* with Disability and eHMI (formula: WouldCross Disability * eHMI; dummy-coded with no disability and no eHMI as reference category; see Figure 4). The model included UserID as random effect (formula: 1 |

UserID). The model's total explanatory power is substantial (conditional R2 = 0.78) and the part related to the fixed effects alone (marginal R2) is 0.16. The model's intercept, corresponding to Disability = no and eHMI = no eHMI, is at 1.45 (95% CI [0.11, 2.78], p = 0.033). Within this model:

- The effect of *Disability [yes]* is statistically non-significant and positive (beta = 0.82, 95% CI [-0.94, 2.58], p = 0.361; Std. beta = 0.82, 95% CI [-0.94, 2.58]).
- The effect of *eHMI [audio]* is statistically non-significant and negative (beta = -5.69e-08, 95% CI [-1.14, 1.14], p > .999; Std. beta = -5.69e-08, 95% CI [-1.14, 1.14])
- The effect of *eHMI [light]* is statistically **significant** and positive (beta = 2.97, 95% CI [1.35, 4.59], p < .001; Std. beta = 2.97, 95% CI [1.35, 4.59]).
- The effect of *eHMI [combined]* is statistically **significant** and positive (beta = 4.31, 95% CI [2.23, 6.40], p < .001; Std. beta = 4.31, 95% CI [2.23, 6.40]).
- The interaction effect of *eHMI [audio] on Disability [yes]* is statistically non-significant and negative (beta = -0.53, 95% CI [-2.16, 1.11], p = 0.527; Std. beta = -0.53, 95% CI [-2.16, 1.11]).
- The interaction effect of *eHMI [light] on Disability [yes]* is statistically non-significant and negative (beta = -0.83, 95% CI [-2.94, 1.28], p = 0.440; Std. beta = -0.83, 95% CI [-2.94, 1.28]).
- The interaction effect of *eHMI [combined] on Disability [yes]* is statistically **significant** and negative (beta = -3.72, 95% CI [-6.12, -1.32], p = 0.002; Std. beta = -3.72, 95% CI [-6.12, -1.32]).

Standardized parameters were obtained by fitting the model on a standardized version of the data set. 95% Confidence Intervals (CIs) and p-values were computed using the Wald approximation.

5.4 Open Feedback

From the feedback field in the survey, some substantial comments have been provided. Aside from expressions of general enjoyment [P66, P67, P69, P74, P77, P81, P92], one of the participants emphasized the visual modality and another one the combined modality [P48] to be very useful [P82]. For P81 the task was unclear, while P44 was irritated by the late yielding of the vehicle. P101 mentioned that the lack of eye contact due to a missing driver prevents a positive crossing decision at all. P47 emphasized the superfluousness of motor sounds with regard to a prevalence of electrified and, thus, silent vehicles. During interviews, we noticed some unexpected answers from participants with ID concerning the relation of perceived UX and crossing-decision. While rating the overall UX positively, they still negated the crossing decisions. This effect was stronger with multi-modality eHMIs, which contradicts the ratings from people without ID. We asked two participants with ID specifically about that decision. They responded that, while simple and understandable, they still feel unsafe to cross. Neither could answer why they chose to cross for the visual single-modal, but not for the multi-modal eHMI. This effect can probably be connected to the increased cognitive load described in Section 6.1 or the negativity bias described in Section 6.2.

6 DISCUSSION

Our survey shows that eHMIs improve the interactions with AVs, which is in line with previous studies, e.g. [31, 37, 46, 102]. We showed differences for multi-modal eHMIs for people with ID in terms of both UX and crossing-decision. We identified potential reasons and derived practical implications.

6.1 User Experience of Different Modalities

No significant differences were measured between no eHMI and the auditory eHMI, but an obstructive tendency of the auditory eHMI could be noticed. This corresponds to the results of other comparative studies on eHMIs [2, 9, 29] and implies that eHMIs should not rely on single-modality signaling only. Furthermore, no significant differences were measured between visual and combined-modality eHMIs. This was visible for both hedonic and pragmatic quality, with a stronger effect in the pragmatic ratings. Considering the baseline and auditory as the lower-quality group and the visual and combined as the higher-quality group, three statements can be made:

- There is no significant benefit of the application of solely auditory eHMIs. Therefore, auditory eHMIs should be used in combination with other modalities.
- For VIP, where visual eHMIs have limited or no effect, combinations of different modalities should be applied to support multiple groups of EVRU simultaneously.
- In summary, the application of multi-modal eHMIs shows positive effects from the quality and the inclusion aspect. Thus, mixed-modality eHMIs should be a general target.

This trend is only contradicted by one data point: The pragmatic quality of multi-modal eHMIs was rated slightly worse than pure visual eHMIs by people with ID. A reason could be that people with ID have less available working memory compared to the average person [72, 95], thus the higher cognitive load caused by simultaneous stimuli [67] leads to worse ratings.

To summarize the UX aspect of RQ1, single-modality visual eHMI concepts show better hedonic and pragmatic quality for both investigated groups than pure auditory concepts or the baseline. Concepts with combined modalities perform significantly best in hedonic quality for both groups, but the pragmatic quality performs worse than the visual single-modality concept for people with ID, while still performing best for people without it.

6.2 Influence on Crossing–Decision

Single-modality eHMIs rather prevent VRUs from crossing (see Figure 4) than they provide support. This contradicts the overall positive quality ratings. This could be explained by the novelty of eHMIs and, therefore, a lack of trust, as people are still unfamiliar with eHMI. Habituation with AVs may improve trust in the systems, leading to better UX ratings and crossing decisions [32, 34, 60]. A later repetition within a longitudinal study also assessing trust could verify this. The results could also indicate that current eHMI concepts are generally not intuitive and need to be revised [11]. Multi-modal eHMIs have been found to improve the crossing-decision significantly, which was verified by some participants (see subsection 5.4). This effect contradicts our collected data and thus calls for further investigation. Negative attitudes towards actions perceived negatively, like entering the lane while a vehicle approaches (so-called *negativity bias* [39]), could be a possible explanation. In summary, the answer to the crossing-decision aspect of RQ1 is that visual single-modality eHMI concepts significantly support crossing decisions for all people equally. In contrast, auditory or no eHMI did not. Multi-modal concepts perform better than visual ones for people without ID, but worse for people with it.

6.3 Different Perception Dependent on Disability

For most modalities, there is no significant difference between the perceived quality, based on the type of ID (see Figure 4). Specific combinations regarding RQ2 resulted in unexpected results: We identified concerns with multi-modal eHMIs, where people with ID rated both pragmatic quality and crossing-decision worse. This could be explained by a higher cognitive load caused by multiple simultaneous stimuli, as already described in subsection 6.1. This suggests that studies on single modality eHMIs with a general participant pool could allow conclusions for people with ID, if the applied survey methods are valid with people with ID. For multi-modal concepts, the UX for people with ID should be measured separately. Our findings of weaker ratings for hedonic and pragmatic quality from people with ID (see Figures 3a, 3b) may result from the interview methodology covered in subsection 6.5. As the values and tendencies are still significant and converge with ratings from people without ID, this does not limit the validity of the results.

6.4 Practical Implications

The perceived UX from people with ID peaked in pragmatic quality for visual eHMIs (see Figure 3b). As our presented concept has been proven easily understandable, we recommend using a visual modality when targeting people with ID. As VIP do not benefit from visual eHMI, but combined eHMI perform worse on people with ID, no general recommendation can be made. However, this should be further investigated. Like co-designing eHMIs for people with impairments like people in wheelchairs [4] or VIP [18], our findings could support developing co-design concepts for people with ID. To our knowledge, no co-design concept has yet been presented for the "Impairment" class of EVRU (in layer 7 of the classification of Holländer, Colley, et al. [49]). Thus, taking people with ID into account when designing eHMIs is crucial for inclusive design creation. We emphasize that our results show that people with and without ID see the same benefits in different eHMI concepts. This suggests that designing eHMI concepts inclusively by applying universal design [40] is beneficial over designing many specialized solutions. However, our findings did not conclude that the strict application of universal design rules always leads to accessible concepts. Using methods like co–creation [103] and methods adjusted to the target group's needs is still crucial.

6.5 Limitations

The way of collecting UX data may still have been too complicated for people with ID. While the questionnaire was answered with support to improve understandability, this opened up the potential for interviewer- or authority-bias [80]. Additionally, using smiling faces for the selection made the questionnaire susceptible to the person-positivity bias [87], meaning people tend to select anthropomorphic over abstract elements.

Although we did not conduct post-test interviews, some participants and caregivers conducting interviews provided feedback on the survey administration. Some expressed concerns that the used smiley faces might not be understandable by all participants withID. As this emphasizes the need for adequate interviewing processes, further adjustments on the UEQ-S need to be made for future applications. Given the presented videos are short (12 seconds), the immersion of the presented scenarios could be enhanced, possibly by using virtual reality (VR). With this approach, we will also aim to reproduce the results scaled up to more realistic scenarios.

Some participants reported problems with the auditory eHMI: depending on the participants' speakers, the audio was distorted, not at all or barely audible, or perceived rather as a warning than a notice (*"You may cross now"*), which confused them. These problems should be targeted in future studies, thus improving all single and combined audio elements.

As we executed the survey online without real traffic, the portability to a real-world scenario is difficult to assess. Additionally, only subjective measurements were used. Nonetheless, we argue that the results provide first quantitative insights on the UX of current eHMIs for people with ID.

Finally, the effects of scalability [21] (i.e., multiple pedestrians or multiple vehicles) were deliberately not evaluated in this first work.

7 CONCLUSION & FUTURE WORK

In this paper, we presented one of the first studies of eHMIs with participants with (*n=64*) and without (*n=56*) intellectual disabilities. We evaluated how people rate selected eHMI based on a cross-section of published concepts and created 3D simulations for those concepts in single- and combined modality as well as a baseline without eHMI. We created an accessible online questionnaire, enabling people with ID to participate by applying specialized interview technologies. We were able to show that the perceived UX and influence on the crossing decision of eHMIs are the same for people with or without ID. For this novel approach, we were able to recruit a considerable sample size of 64 people with some kind of ID and a control group of 56 people without ID. As we focused particularly on providing equal conditions adjusted to the individual abilities, in order to rate selected eHMIs for people with ID, we were able to collect comparable data on the perceived UX of eHMIs.

We further discovered a discrepancy from previous work rating UX of multi-modal eHMIs [2, 54]. While generally rated as more beneficial than single-modality concepts, they perform significantly worse for people with ID than visual single-modality ones.

With the gathered insights into the interactions of people with ID, our work helps to safely introduce AVs into the general public while supporting the specific needs of people with ID. We believe this is one step towards more inclusive automated traffic.

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We applied the FLAE approach to the sequence of authors.

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A INTRODUCTION TO SCENARIO

Dear participant, welcome to my survey. My name is Mathias Haimerl. I am researching in the field of self-driving cars and how they communicate with people. In my first study, I want to find out, if the ideas of other researchers are already appropriate for people with handicaps, or if there is still a lot to be changed. For the survey, you are first asked for data to assess your capabilities, characterize you scientifically, so to speak, without us needing to have your personal data. On the following pages, you will see videos of cars that recognize you want to cross the street and signal you in different ways that they will yield for you. You should just rate how you found the individual types, so, how you felt. Thank you very much for participating and I hope it is also a little fun.

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