Designing for Automated Vehicle and Pedestrian Communication: Perspectives on eHMIs from Older and Younger Persons

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Abstract

The automation of automobiles requires much theoretical, legal and empirical work in order to define and ultimately resolve the complexities associated with it. One of the many challenges that automotive manufacturers face is how driverless, automated vehicles will communicate to other traffic participants. This issue is especially crucial for vulnerable road users such as pedestrians, where the consequences of miscommunication are potentially critical. One possible way for automated vehicles to communicate to pedestrians besides their movement behaviour is through an external human-machine interface (eHMI), where an explicit, informative message in the form on an icon (static) or dynamic animation, for example, is presented outside the vehicle. In this paper, we report the subjective results of an experiment investigating four different eHMI concepts in two age groups (20-30 and 60-70 years old). The participants were exposed to the concepts in an immersive, virtual environment, consisting of three different traffic scenarios, presented on a head-mounted display. The aim of the subjective inquiry was to understand the participants' preferences regarding the investigated eHMIs experienced as well as their suggestions regarding improvements. Overall, participants preferred dynamic messages over static ones.

Introduction

With the increasing automation of vehicle control, the progressive complexity of traffic scenarios and interaction between road users, new possibilities are being considered to facilitate the communication between road users (Färber, 2015, Fekete, Vollrath, Huemer & Salchow, 2015; Zimmermann, Fahrmeier, Bengler, 2015). However, this issue has not yet been thoroughly, empirically investigated. Current research mainly focuses on, for example, CarXCar or environmental information acquisition (Federal Ministry of Transport and Digital Infrastructure, 2015) or the interaction between automation and vehicle occupants (Bendewald, Stephan, Petermann-Stock & Glaser, 2015; Othersen, 2016). Higher levels of automation also raise many unanswered questions, including: how could nearby human road users communicate and interact with automated vehicles or how may

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current communication strategies be affected by the use of automated and driverless vehicles. Mostly, in conventional road traffic, an informal communication takes place in the form of non-verbal communication, e.g., gestures, facial expressions, and eye contact (Färber, 2015). These ways of communicating will no longer be available to pedestrians when autonomous vehicles are used due to the lack of a human driver. However, it can be assumed that the other road users' need for information will not change in the first steps of the introduction of such a system (Färber, 2015).

Communication between a vehicle and a vulnerable road user (VRU, e.g., a pedestrian, cyclist, etc.) is of particular interest and must be examined more closely as a potential area of conflict with regard to higher levels of automation. The improvement of traffic flow and traffic efficiency has been specified as a potential benefit of automated and driverless vehicles (Friedrich, 2015). Studies have shown that pedestrians do not simply step in front of a vehicle but rather closely observe vehicle behaviour and safely adapt their own actions to that of the vehicle (Schweizer et al., 2009). The most important influencing factors are speed (Schneemann & Gohl, 2016; Habibovic et al., 2018), distance (Schneemann & Gohl, 2016; Habibovic et al., 2018), clear deceleration of the vehicle (Schneemann & Gohl, 2016), as well as vehicle behaviour and motion (Cramer, Siedersberger & Bengler, 2017; Habibovic et al., 2018). A study by Šucha (2014) revealed that 46% of participants waited for a vehicle to come to a complete stop and 84% sought eye contact with the driver before crossing the road. In crossing scenarios, the potential for an increase in traffic flow due to automated vehicles would therefore be obsolete or limited.

The objective of external communication is to facilitate symbiotic actions between road users and the recognition of intentions by displaying a current HMI on the exterior of the vehicle (external Human Machine Interface – eHMI). This could increase the cooperation between road users in manual and assisted driving and represent new communication channels for automated and driverless driving. In this context, new HMI components that make it easier for drivers or a VRU to communicate with other road users are being designed. Initial research looked at visual indicators on the exterior of a vehicle. These indicators comprised either displays or lighting elements on the front area of the vehicle (Lagström et al., 2015; Clamann et al., 2016; Fridman, Mehler, Xia, Yang, Facusse & Reimer, 2017).

In the reported experiment, the interaction between informal communication between pedestrians and vehicles, pedestrians' adjustment of their road-crossing behaviour, and the clarity of the messages are investigated. The underlying research question in this paper is: What influence does a display-based eHMI have on pedestrians' road-crossing behaviour? The content of the information, which can be displayed as either a lighting element or symbol, plays a particularly important role. Therefore, the aim is to identify road-crossing behaviour and to subjectively evaluate different variants of a visual indicator in a study conducted in a pedestrian simulator. In addition, the potential effect of age is considered in this study.

Methodology

Study setting and study design

The study was carried out in the pedestrian simulator at the Technical University of Munich (for more information on the simulator, see Dietrich, Willrodt, Wagner, & Bengler (2018)). The participants carried an HTC VIVE, which has two OLED displays with a resolution of 1080 x 1200 pixels, as a head-mounted display. A workstation (CELSIUS M740B Power) with an Intel Xeon-E5-1620v4 (3.5 GHz) processor, 16 GB DDR4 RAM (2 400 MHz), and NVIDIA Quadro M5000 graphic cards with 8 GB VRAM was used. To allow participants to feel as immersed as possible, real environmental sounds stemming from the laboratory were suppressed and sounds from the virtual world were played to the participants using BOSE noise-cancelling headphones. Unity 3d was used as the simulation software. The virtual environment resembled an inner-city situation from Munich. The roads were based on German standards with a width of 3.25 metres. The participants were able to move freely within an area of approximately 3 x 5 metres, and a blue grid was displayed to the participants to mark the end of this accessible area.

A 2x2x3x2 mixed design was used for the trial, with the following factors:

- eHMI type (lighting element vs. symbol)
- eHMI dynamics (static vs. dynamic)
- Scenarios (scenario A: 30 km/h on a straight road; B: 50 km/h on a straight road; and C: 30 km/h with a right turn)
- age groups (older vs. younger)

The last factor was the only “between” factor, so the participants were naturally divided into two age groups (older: 60-70 years, and younger: 20-30 years). The eHMI type, eHMI dynamics, and scenarios were implemented as a “within” design. The eHMI differed with regard to the type of display (eHMI type: lighting element vs. symbol) as well as the level of animation (eHMI dynamics: static vs. dynamic). Each display variant was shown in three different situations. In addition, each scenario was repeated without eHMI in order to collect baseline data for each scenario (baseline condition). The participants were given the task of crossing the road after the first vehicle. Following traffic showed variable gap distances in between the vehicles. Participants were introduced to cross whenever they felt safe in doing that. However, a certain vehicle in the line of traffic came to a complete stop and, where appropriate, communicated via the eHMI. The deceleration strategy of the yielding vehicle was identical within each scenario but the number of vehicles the participants could not cross in front of was pseudorandomised (a precise description of the study scenarios can be found in Dietrich, Othersen, Maruhn, Conti-Kufner & Bengler, 2018).

eHMI

For a better evaluation of the complexity of the information and the communication strategies, two different designs were used in the study (factor: type). Each design was displayed as a static and as a dynamic display (factor: dynamics). The static display was primarily used to express the information "I have seen you," and the dynamic display was more an illustration of the information "you may now cross the road in front of me." Thus, these two types (see figure 1) had an effect on the communication strategy and complexity.

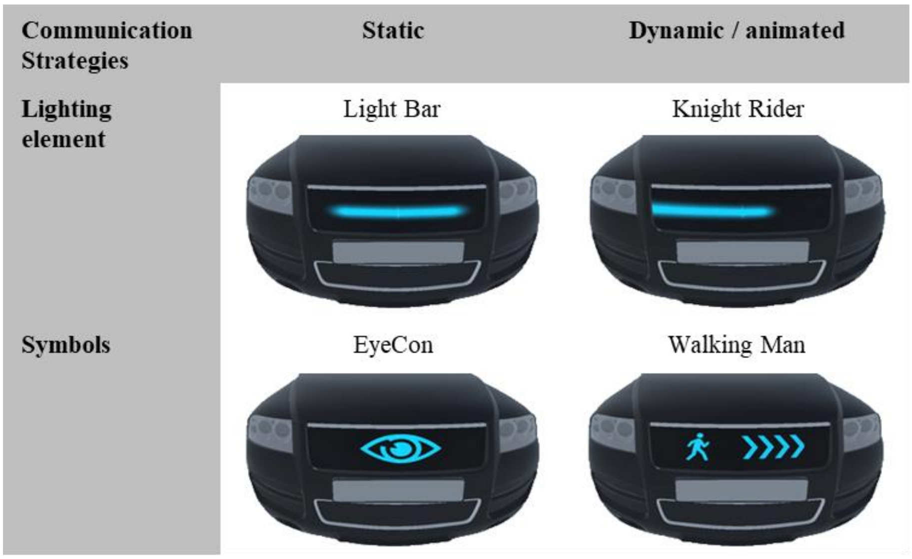


Figure 1. Types of communication strategy with the two "between" factors: type and dynamics

In the light-based design, a virtual LED bar was integrated into the grille. This variant approximated the various lighting designs (see Ritter, Adikari & Nagel, 2017). The static variant lights up once the vehicle is 50m away from the pedestrian and is deactivated again after the interaction has come to an end. In the dynamic variant of the light-based design, the LED bar was shown as a chaser light with a repeated sequence from left to right, indicating the crossing direction to the addressed pedestrian. A symbol-based design by Volkswagen Group Research was developed as a second design. In the static variant, an eye was shown, indicating that the pedestrian was perceived by the yielding vehicle. In the dynamic variant, a pedestrian was shown in a walking animation augmented by four animated arrows. It also included directional instructions to cross from left to right.

Procedure

Participants first filled out a demographic questionnaire and consent form. The participants were then introduced to the experimental procedure and VR pedestrian simulator. Prior to the experiment, height measurements of the participant were taken and their vision was assessed (colour vision and virtual reality visual acuity). Participants were instructed to cross the street whenever they felt safe to after the first vehicle has passed them. Additionally, participants were informed that some vehicles have a display, which enables them to communicate with their environment. Participants trained the crossing task in the VR environment until they reported to feel comfortable with the task/environment and the experimenter judged their performance as satisfactory. The experiment was divided into three different blocks, representing the different tested scenarios: A, B, and C. Blocks and eHMIs were permuted for each age group. Between each block, participants were given a break and filled out a short questionnaire of whether they had any positive or negative feedback regarding the scenario or eHMIs experienced in the past block. After all blocks were completed, final questionnaires were administered to participants. The experimental session lasted approximately one hour.

Data and analysis

The current paper presents the results from different questionnaires given to participants during and at the end of the experiment as well as a short insight in the objective variable of crossing initiation time to vehicle stop (CIT_{VS}) (for a detailed analysis see Dietrich, Othersen, Maruhn, Conti-Kufner & Bengler, 2018).

Various metrics to measure traffic efficiency on a macroscopic level or the severity of potential conflicts are widely utilized today to understand urban traffic. However, to quantify a pedestrian's reaction to a yielding vehicle requires a metric for unhazardous situations. The crossing initiation time to vehicle stop is included in this paper as a metric to enable an objective evaluation of the participants' subjective statements. The CIT_{VS} is the difference between the time, at which the vehicle comes to a full stop and the time at which the pedestrian initiates his/her crossing (measured when the participant's head moved 70 cm in crossing direction). If this value is negative, it means that the participant started to cross the road before the vehicle came to a standstill.

Several open questions, the User Experience Questionnaire (UEQ) created by Laugwitz, Schrepp & Held (2008) and an eHMI variant ranking, which were presented to the participants in the final interview, were used as a subjective data.

The aim of the open questions was to understand the participants' preferences regarding the eHMIs presented as well as their point of view in terms of improvements. To this end, participants were asked to respond to 5 open-ended questions (the following has been translated from German):

- What did you like about the eHMI? Please explain your answer.
- What did you not like about the eHMI? Please explain your answer.
- If you could change something about the eHMI, what would you change (e.g., so that it would be clearer or more attractive)? Please explain your answer.
- Do you have suggestions for improvements for the eHMI (e.g., should it be presented somewhere else or should it look different?)? Please explain your answer.
- Which modality would you prefer for an eHMI (e.g., visual, acoustic, multimodal, other)? Please explain your answer.

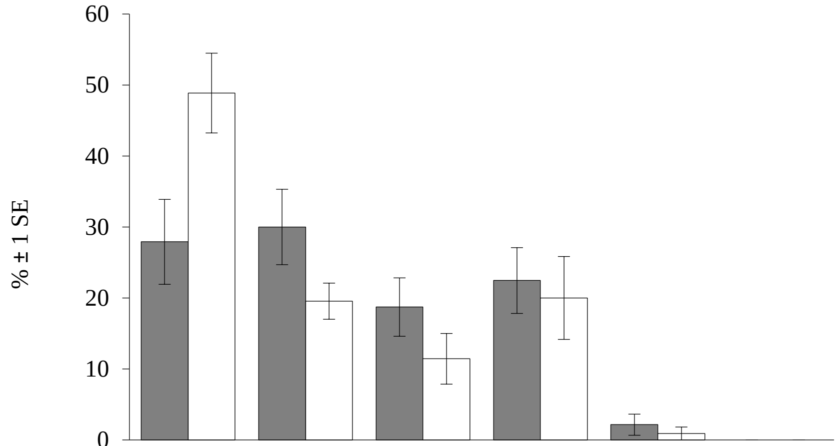
The participants' responses to the open questions were digitally transcribed, encoded and analysed using MAXQDA. In the qualitative text analysis, word and category frequencies were analysed in order to draw conclusions on user attitudes (Mayring, 2000; Mey & Mruck, 2010).

The quantitative data (CIT_{VS}, UEQ, and ranking) were analysed descriptively and using statistical tests, i.e. t-test and 3 (scenario) x 5 (eHMI) x 2 (age group) mixed ANOVA with scenario and eHMI as within subject factors (overall four eHMI variants depicted in fig. 1 plus one baseline condition) and age group as between subject factor.

Participants

A total of 43 participants (N) participated in this study. The average age of the older group (60-70 years, n = 21, 43% female) was 64.7 years, and the average age of the younger age group (20-30 years, n = 22, 45% female) was 24.3 years.

Both groups were also asked about their usual mobility behaviour, e.g. the type of means of transportation used and the number of daily road crossings, and their communication in traffic, e.g. the number of daily interactions via glances, gestures and facial expressions. With regard to the mobility behaviour (see figure 2), the younger group used public transport most frequently, followed by car, and then travelling on foot or by bicycle. In contrast, the older group travelled most frequently on foot, followed closely by public transport, and then by car. Therefore, members of the older group are more likely to be involved in traffic as vulnerable road users.



	Public Transport	Foot	Biking	Car	Motor-bike	Other
older group	27,90	30,00	18,71	22,45	2,14	0,00
younger group	48,86	19,55	11,43	20,00	0,91	0,00

Figure 2. Modes of transport, separated for the two age groups: older (60-70 years) and younger (20-30 years).

However, both groups indicated that they cross a road in traffic more or less equally often. In the two groups, approximately 46% do so often, approximately 46% sometimes, and 8% rarely. This indicates that younger road users either participate less in road traffic as a pedestrians, but do more road crossings on average than older road participants or that the older participants were more restrained when answering the questionnaire. In addition, the participants were asked about how often they communicate in traffic using glances, gestures, and facial expressions. The older group report using such non-verbal communication more often (43% often, 48% occasionally, and 9% rarely) than the younger group (23% often, 41% occasionally, and 36% rarely).

Results and subjective insights

Crossing initiation time to vehicle stop (CIT_{VS})

The road crossings of the 43 participants, of which 34 completed all conditions[1], were compared in order to identify the effect of the different eHMI variants compared to one another and to identify a baseline for their road-crossing behaviour. There were no interaction effects between Scenario, Age Groups and eHMI variant. A main effect analysis shows that there is a significant effect of the eHMI variant on the CIT_{VS} ($F(4, 29) = 25.58$, $p = .000$, $\eta_p^2 = .78$). A Bonferroni post hoc test revealed significant differences between the crossing initiation times in the baseline condition (mean value of 1.07s, SD=0.99s) compared to the eHMIs (EyeCon 0.39s ± 1.14s, Knight Rider 0.23s ± 1.27s, Light Bar 0.52s ± 1.15s & Walking Man 0.15s ± 1.10s). These results indicate that participants started crossing the road earlier if there was an eHMI presented. Furthermore, the CIT_{VS} is smaller with dynamic eHMI displays, i.e. Knight Rider and Walking Man, than with static ones (see figure 3). The data also revealed that 28% of the participants crossed the street before the vehicle came to a full stop when the approaching vehicle had in eHMI equipped in comparison to 9% without an eHMI.

There was a significant effect of the scenario where participants encountered the traffic conditions on their CIT_{VS} ($F(2, 31) = 7.21$, $p = .003$, $\eta_p^2 = .32$). A Bonferroni post hoc test showed that the crossing initiation time in scenario A (30km/h, straight road: 0.22s ± 1.24s) was significantly lower compared to scenario B and C (50km/h, straight road: 0.59s ± 0.99s; 30km/h, right turn: 0.71s ± 1.19s).

No difference in CIT_{VS} between the two age groups was found ($F(1, 32) = 0.05$, $p = .820$). Older participants had a CIT_{VS} of 0.54 seconds (*SD*=1.16) compared to 0.47 seconds (*SD*=1.16) of the younger participants.

[1] The yielding vehicle fully stopped for 2 seconds before accelerating again. Nine participants did not initiate a road crossing in time. Therefore 34 from 43 participants were included in the statistical analysis.

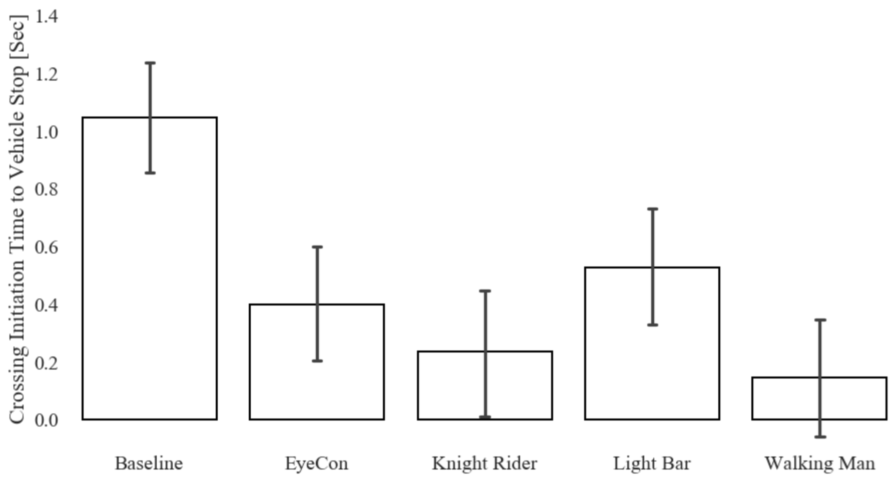


Figure 3. CIT_{VS} for the baseline conditions and the eHMI variants (95 CI for the mean).

Open questions

The final evaluation open questions (questions 1 and 2), which asked about positive impressions and suggestions for improvement, resulted in more positive than negative comments. The responses to these questions were assigned to one of the following categories: Understandability, Perceptibility, Appeal, Safety, and Other response (see tables 1 & 2).

The “Walking Man” eHMI was mentioned in 23 responses and achieved the most positive responses for the categories Understandability, Perceptibility, and Appeal in both age groups. In particular, it was positively commented that the dynamic display clearly signalled the vehicle's intention and enabled the next action to be inferred. Likewise, the dynamic “Knight Rider” eHMI was positively evaluated and received a total 17 mentions in the same categories.

- Example regarding “Walking Man”: *“It provides security and confirms to pedestrians/me that I can safely cross the road. I found the dynamic variants intuitively easier to understand. I found the size of the display to be just right. Pictograms are good.”* (younger participant; translated from German)
- Example regarding “Knight Rider”: *“Dynamic displays could be perceived early, and you understood in which direction pedestrians were recognised/could go. Over time, you become confident that cars with displays will really stop for you, and you gain confidence. It is good that it is always consistently in blue tone.”* (older participant; translated from German)

Table 1. Frequency of positive and negative statements for questions Q1 & Q2 separated by age group – Categories "Understandability," "Perceptibility," "Appeal" (y: younger group; o: older group)

	Understandability				*Perceptibility*				*Appeal*			
	positive		*negative*		*positive*		*negative*		*positive*		*negative*	
	y	*o*	*y*	*o*	*y*	*o*	*y*	*o*	*y*	*o*	*y*	*o*
Knight Rider	4	3	1		3	1		1	4	1		1
Walking Man	6	4			5	1			5	1		1
EyeCon			5	2			1	2			5	1
Light Bar			5	2			2	3			3	1
Other response	5	6	2	3	4	1	3	1	2	4		1
Overall	**15**	**13**	**13**	**7**	**12**	**3**	**6**	**7**	**11**	**6**	**8**	**5**

Table 2. Frequency of mentions in positive and negative statements for questions Q1 & Q2 separated by age group – Categories "Safety" and "Other" (y: younger group; o: older group)

	Safety				*Other*			
	positive		*negative*		*positive*		*negative*	
	y	*o*	*y*	*o*	*y*	*o*	*y*	*o*
Knight Rider					1			
Walking Man					1			
EyeCon								
Light Bar								
Other response	8	6	1	2	9	3	7	1
Overall	**8**	**6**	**1**	**2**	**11**	**3**	**7**	**1**

In contrast, the "EyeCon" and "Light Bar" eHMIs were only given suggestions for improvement, as the content was not considered informative, or immediately and clearly perceptible. In addition, the participants stated that it was difficult for them to see the static displays relating to the vehicle status or the future behaviour of the vehicle.

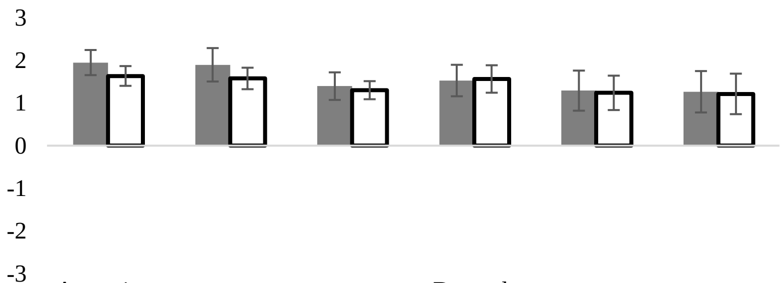
- Example regarding "EyeCon*": "The static displays attract your attention less, are easier to overlook..."* (older participant; translated from German)
- Example regarding "Light Bar": *"The static displays without arrows are hard to understand, you have to think about them a lot. Possible distraction for oncoming traffic."* (younger participant; translated from German)

Overall, the participants were able to give additional free comments that did not explicitly relate to one of the eHMI variants (question 3 & 4). In particular, the eHMIs' potential ability to contribute to the pedestrians' subjective feeling of safety and trust by clearly displaying a vehicle's status and facilitating the anticipation of vehicle behaviour was mentioned as positive in the Safety category. For the above reasons, large (22% of younger participants and 14% of older participants) and multi-coloured symbols (19% of younger participants and 23% of older participants) with a dynamic display were mentioned and evaluated as quickly learnable. The negative comments mostly referred to a possible familiarisation effect, which could lead to a certain insecurity with vehicles without eHMI. The position on the vehicle and the risk of confusion with the regular lighting were also mentioned. Younger participants recommended using the complete radiator grille exclusively for the eHMI. In contrast, the older participants suggested a completely new location, e.g., in the area of the windshield based on the visual axis to today's drivers in this area.

In response to the question on the type of eHMI (question 5, multiple responses possible), the participants stated that a visual display was their main preference (60% of younger participants' responses and 50% of older participants' responses). A multimodal design was positively evaluated by 36% of younger participants and 44% of older participants. On the one hand, environmental conditions were given as reasons for this ("Several modalities are imperative, as depending on the time of day and how much sun there is, purely visual displays are not always easy to see.") and, on the other hand, impairment or distraction of people was mentioned ("With a visual/acoustic design, you can reach everybody – including blind and deaf people.", "If you are wearing headphones or are looking at your mobile phone, you can still be contacted."). A purely acoustic design only received one vote per age group.

UEQ and ranking

The UEQ showed a positive evaluation for the general use of an eHMI with an evaluation over +0.8 points (see figure 4). The evaluation did not differ significantly between the age groups (attractiveness: t(37) = -1.65, p = 0.11; efficiency: t(37) = 0.63, p = 0.63; perspicuity: t(37) = -1.36, p = 0.18; dependability: t(37) = 0.15, p = 0.86; stimulation: t(37) = -0.17, p = 0.87; novelty: t(37) = - 0.15, p = 0.88).



	Attractive-ness	Perspicuity	Efficiency	Depend-ability	Stimulation	Novelty
older group	1,95	1,89	1,39	1,53	1,29	1,26
younger group	1,63	1,58	1,30	1,56	1,24	1,21

Figure 4 UEQ scores, separated for the two age groups: older (60-70 years) and younger (20-30 years).

Finally, the test persons were able to give an all-over evaluation by a ranking the four eHMIs. The ranking likewise showed a preference for the dynamic displays followed by the static displays. The eHMI with the dynamic symbol was ranked first, followed by the dynamic lightning element in second place. There was very little difference between third and fourth places, with third place being taken by the static icon and fourth place by the static lightning element.

Discussion and summary

The aim of this experiment was to investigate the effect of eHMIs on pedestrian experience and road-crossing behaviour. To this end, road-crossing behaviour and the subjective evaluation of the different variants of a visual display for two different age groups were assessed.

The results for road-crossing behaviour, measured using crossing initiation time to vehicle stop (CIT_{VS}), showed that participants crossed the road sooner when an eHMI was used. In addition, data revealed that with an available eHMI 28% of the participants crossed the street before the vehicle came to a full stop in comparison to 9% without an eHMI. Dynamic displays seem to potentially enhance this effect, where no clear difference was observed between the dynamic lightning element and the dynamic symbol. This study in the pedestrian simulator showed first tendencies that the safety behaviour of pedestrians can potentially change with using an eHMI and that the willingness to cross a road potentially increases before the vehicle has come to a standstill. However, as the study was conducted in a VR simulator and only covered somewhat simple scenarios, external validity of the results and the applicability of eHMIs in real world urban traffic needs to be reassessed in future studies.

Positive implications for the use of an eHMI can also be taken from the subjective data, which comprises open questions, the UEQ, and the ranking as an overall evaluation. The eHMIs as a whole were positively evaluated in terms of attractiveness and perspicuity above all in the UEQ. According to participant statements, the eHMI can be understood as a design element, but can also make an important contribution to the understanding of a vehicle's future status. This picture also becomes clear from the categorised responses to the open questions and the ranking. The dynamic displays received predominantly positive responses for the categories “Understandability,” “Perceptibility,” and “Appeal” in both age groups. In contrast, the static displays were not evaluated as immediately and clearly perceptible, and the participants found it difficult to draw conclusions on the vehicle's future status from the static displays. The static displays occupied the last two places in the ranking. As potential improvements, the participants mentioned the use of animations for an eHMI or the use of existing colours or road signs. With regard to a preferred modality, the majority of participants were also in favour of a visual design. However, the participants also saw the advantages of a multimodal design, comprising a visual and acoustic content. In this regard, potential environmental constraints (e.g., weather conditions or interference from the environment) or constraints relating to the recipient themselves (e.g., impairment or distraction of people) play a decisive role.

This experiment was able to show that the use of an eHMI could generate potential benefits for interactions with an automated or driverless vehicle, e.g., an increased feeling of safety and quicker road-crossing behaviour. This enables optimal adaptation of the human-machine interaction to the new form of communication. However, further studies are required to investigate additional display options and other scenarios. It is also necessary to look in more detail at road-crossing and hedging behaviour depending on speed, distance, and vehicle movements, as these factors appear to have a significant effect (Cramer, Siedersberger & Bengler, 2017; Habibovic et al., 2018). Future experiments should also consider to be conducted in real driving environments to ensure validity.

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