Towards user acceptance of autonomous vehicles: a virtual reality study on human-machine interfaces

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Abstract: Technological advances in businesses related to automated transportation raise challenges. Indeed, ensuring safety for users is essential for the future commercial launch of this technology. Within this study, human-machine interfaces (HMIs) are evaluated regarding the communication between autonomous vehicles (AVs) and pedestrians in order to prepare a successful deployment of the technology on the market. Since real-life experiments involving AVs remain dangerous, experiments were conducted via virtual reality (VR). The results show that beyond the need for HMIs, display-based concepts were more usable than laser projections. The study impacts on: 1) substantiating the need for explicit HMIs on AVs (including concept recommendations) for a successful market entry; 2) proving that VR constitutes an advantageous alternative for conducting experiments in the field of autonomous transportation for both research and business. Further work is needed that involves more participants and an improved virtual environment.

Keywords: virtual reality; autonomous mobility; human-machine interfaces; HMIs; usability testing; pedestrian safety; pedestrian simulator; pedestrian behaviour; evaluation of interfaces; head-mounted display.

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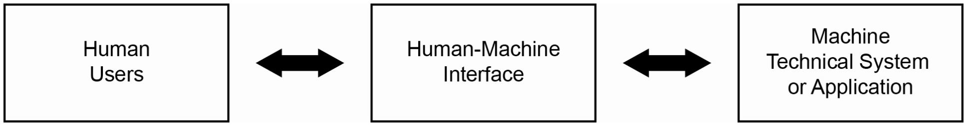
1 Introduction

Research in the automotive industry constantly progresses towards full automation. A prognosis by IHS Automotive (2014) predicts level 5 (fully) autonomous vehicles (AV)[1] to be implemented into daily traffic by 2030. It is forecasted that advances of automation technology will highly impact economy (i.e., efficiency and business opportunities) as well as safety (i.e., less traffic accidents) (Lanctot, 2017). Nevertheless, technological advances lead to challenges in terms of user acceptance. The communication between manually driven vehicles and pedestrians especially in ambiguous situations, such as at zebra crossings or in car parks, are currently executed mainly via gaze and gestures (Llorca et al., 2011; Šucha, 2014; Charisi et al., 2017). Since there is no driver in a level 5 AV, this communication cannot be carried out in the same manner anymore. The absence of communication increases concerns about sharing streets with AVs as a human road user (HRU), especially as pedestrian or cyclist. This retrospectively hinders user acceptance and results in safety hazards (Bikeleague, 2014). Therefore, the present study aims to find out whether human-machine interfaces (HMIs) can compensate this lack of communication, and thus encourage user acceptance.

HMIs are communication channels that enable the interaction between human users and a machine (Johannsen, 2009). Figure 1 shows the definition of a human-machine system according to Johannsen (2009) that encompasses all aspects of interaction between the human and the machine.

Figure 1 The human-machine system



Source: Adapted from Johannsen (2009)

With increased automation of a machine, the need for improved human-machine communication (including interfaces) increases correspondingly (Johannsen, 2009). For the present study, this means that the increase of automation of vehicles must entail suitable HMIs to ensure user acceptance.

Several methods and models that involve users for the evaluation of HMIs exist. Literature reviews (Chandra et al., 2010; Taherdoost, 2018) list among others the theory of reasoned action (TRA) (Fishbein and Ajzen, 1975), the theory of planned behaviour (TPB) (Ajzen, 1985; Ajzen and Madden, 1986), the technology acceptance model (TAM) (Davis, 1989; Davis et al., 1989), the theory of diffusion (Moore and Benbasat, 2009), the institutional theory (Liang et al., 2007; Teo et al., 2013), and the pairwise comparison-based preference measurement (PCPM) (Meißner et al., 2010; Scholz et al., 2010) under these models. All of these methods have limitations as soon as the evaluation includes future technologies (like AVs) that are not deployed on the market yet. For example, testing user experiences with AVs in real-life conditions would lead to the following major challenges:

- safety, since wrong behaviours from the AV or participant during the experiment could lead to accidents
- complexity in the creation of an authentic traffic scenario including AVs and HRUs
- reproducibility of the experiment to ensure that every participant faces the same conditions,
- time, cost and effort connected to building up and conducting the experiment.

To counter these issues, the researchers of the present study conducted user experiments in virtual reality (VR) as an alternative to real-life experiments to evaluate a set of HMI concepts for AVs. The study focuses on finding out:

1. if explicit[2] HMIs are necessary for the communication from AVs to HRUs in ambiguous traffic situations (research question 1)
2. which displayed information and technology of HMIs are most supportive for the communication from AV to HRUs in terms of displayed information and technology for information transmission (research question 2).

2 Literature review

2.1 HMIs for autonomous vehicles

Car manufacturers like BMW, Mercedes, Nissan, and Toyota conduct research on AVs with automation level 4 (high automation for some driving modes) and 5 (full automation). Figure 2 shows concepts of Mercedes (F 015) and Smart (vision EQ for two) that include potential channels for future communication between AVs and pedestrians (Mercedes Benz, 2015; Daimler, 2018). While one of the concepts uses a laser projection on the street in front of the AV (left picture), the other concept is equipped with a screen at the front of the vehicle that shows information (right picture).

Figure 2 (a) Mercedes F 015 (b) SMART vision EQ for two (see online version for colours)

(a) (b)

Source: *Mercedes Benz (2015) and **Daimler (2018)

Table 1 Overview of published explicit HMI concepts

1	*2*	*3*	*4*	*5*
Name/brand	*Level of automation*	*Description*	*Technology*	*Semantics*
Mercedes F015 (Mercedes Benz, 2015)	4	Laser projection on the street; Display and sound show the AVs intention and give instructions	Display Laser Sound	Symbols Text
Nissan IDS (Nissan, 2015)	4	LED strip shows detection and display gives instructions	Display LED strip	Text Light
Toyota Concept-I (Toyota, 2017)	4	Display shows intention and headlights show detection	Display Headlights	Symbols Text
Rinspeed Oasis (Rinspeed, 2017)	4	Laser projection on the street gives instructions	Laser	Text
VW I.D. (Volkswagen, 2016)	4	LED headlights show detection and gives instructions	Headlights	Symbols shown via the LED headlights
Navya Autonom Shuttle (Navya, 2016)	5	Display shows intention and instructions	Display	Symbols Text
LeEcoLeSee (Business Insider, 2016)	4	LED strip shows instructions	LED strip	Light
BMW vision next 100 (BMW, 2016)	4	Light sculpture shows detection and gives instructions	Light sculpture and strip	Light
Waymo One (Waymo, 2015)	4–5	Display shows instructions	Display	Symbols Text
Nio Eve (Nio, 2017)	4	LED strip gives instructions	Light strip	Light

Table 1 Overview of published explicit HMI concepts (continued)

1	*2*	*3*	*4*	*5*
Name/brand	*Level of automation*	*Description*	*Technology*	*Semantics*
Audi Matrix Laser headlights (Audi, 2015)	N.A.	Headlights give instructions through light beams	Headlights	Light
AEVITA (Pennycooke, 2010)	4–5	Display shows intention and detection	Display	Symbols
Smartvision EQ for two (Daimler, 2018)	4	Display shows intention and instructions	Display	Symbols Text
Mitsubishi forward indicator (Mitsubishi Electric Corporation, 2015)	4–5	Laser shows intentions	Laser	Symbols

Table 1 shows a comparison of vehicle and system concepts that focus on the communication between AVs and HRUs.

The majority of concepts shown in Table 1 do not have proof of concept especially in the actual application field. To the authors' best knowledge, the only published scientific validation experiment is the AEVITA moving headlights by Pennycooke (2010) in which the author concluded the necessity of explicit communication channels for AVs. Overall, it remains unclear to which extent the HMI concepts are supporting the communication from AV to HRUs, especially in ambiguous situations and furthermore, which technology is the best channel for this communication.

2.2 Evaluating user acceptance of HMIs

This section reviews different methods, models and studies that exist for the investigation of user acceptance of new technology with a focus on the case study 'HMIs for communication from AV to HRUs'. Starting with the widely used TAM, which investigates how intended users (i.e., potential customers) may adopt a new technology, the review enlarges the scope to studies that consider all users who will be confronted with the new technology on the street. Finally, the review focuses on specific methods used for evaluating HMIs that have their roots in computer sciences.

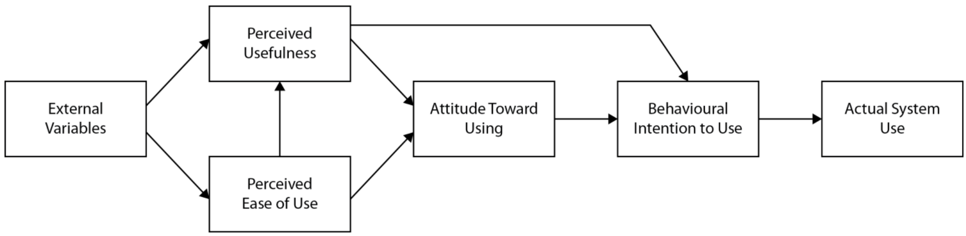
2.2.1 User acceptance of new technology: the TAM

Prediction of user acceptance is of major importance at the beginning stage of businesses for developing successful products and services. Several models and methods have been developed to predict the acceptance of new technologies.

The TAM is perceived to be the most widely used and robust model to predict the user adoption of new technology (Kesharwani and Bisht, 2012) in information system research. Moreover, it is anticipated that the TAM is more suitable than its extended versions in this exploratory scope [Rauschnabel and Ro (2016) based on Bagozzi (2007)].

The TAM hypothesises that 'perceived usefulness' (related to improvement of a task performance) and 'perceived ease of use' (related to achievement of a task without effort) influence the 'attitude towards using' a product or system depending on external variables, which induces the 'behavioural intention to use' (Davis, 1989; Davis et al., 1989). This process leads to the ‘actual use of the system’ and subsequently to the acceptance of technology [Figure 3 (Davis, 1989)].

Figure 3 Technology acceptance model



Source: Davis (1989)

In the present case study of HMIs for the communication from AV to HRUs, the attributes ‘perceived usefulness’ and ‘perceived ease of use’ are central since these interfaces are made to support a performant and effort-free decision-making of pedestrians while crossing a street. However, the additional steps that are linked with the direct use of the system are not transferrable to the case study: the HRUs who are confronted with the interfaces are not directly using the system (no control of the AVs) but receiving information that supports their decision-making for crossing a street. Furthermore, performance and effort required for understanding HMIs need to be considered for *all* HRUs and not only the intended users (i.e., potential customers).

Several studies have been conducted to understand user acceptance of new technologies related to AVs and are described in the following section.

2.2.2 User acceptance of AV technology

When new technology is involved, the first obstacle for evaluating its acceptance by the user is the lack of prototype. In the present case study, AV prototypes are not availableon the market yet and therefore, evaluating them requires other techniques than those involving physical prototyping. In the context of acceptance of AV technology, studies have been found that use:

- structured questionnaires
- Wizard-of-Oz experiments
- VR experiments.

Several studies used structured questionnaires for data collection to investigate the general attitude towards AVs and how trustful this technology is perceived at the time of the study (e.g., do users trust AVs to make critical decisions) (Lagström and Lundgren, 2015; Rothenbücher et al., 2016; Deb et al., 2017b; Dey and Terken, 2017; Matthews and Chowdhary, 2017; Zimmermann and Wettach, 2017; Hein et al., 2018; Hulse et al., 2018; Mahadevan, 2018). Using structured questionnaires is a fast and effective way of data collection with little effort involved (Martin and Hanington, 2012). Deb et al. (2017b) developed a pedestrian receptivity questionnaire that includes items based on attitude, trust, social norms, and system effectiveness. The authors stated as one limitation of the study that the results were solely based on participants' responses and not their actual behaviours. The authors anticipated that the responses may have differed from the actual behaviours when interacting with AVs Deb et al. (2017b). This shows an important limitation of exclusively using structured questionnaires as a method for data collection in this context. It is anticipated that one missing key aspect is the lack of imagination and experience from users' side when answering questions for scenarios that are not feasible in real-life conditions yet.

Using the Wizard-of-Oz method means that participants can experience a system that appears to be fully working and real while the researchers perform behind the scenes in order to create the simulation, even though the system is not fully working or functioning yet (Dahlbäck et al., 1993; Martin and Hanington, 2012). This method has been used by several researchers in the context of pedestrian safety to investigate actual participants' behaviour when being confronted with a transport system that appears to be automated (Clamann et al., 2015; Lagström and Lundgren, 2015; Rothenbücher et al., 2016; Dey and Terken, 2017; Matthews and Chowdhary, 2017; Mahadevan, 2018). Clamann et al. (2015) conducted a Wizard-of-Oz study in which participants interacted with an AV that was a disguised manually driven vehicle at a zebra crossing. A major limitation of conducting experiments like the aforementioned one is the lack of safety. Studies show that main safety concerns in pedestrian research are speed of the approaching car and the predictability of pedestrians' behaviours. Both of these aspects are interlinked and interdependent (Šucha, 2014). This implies that even if the vehicle is behaving correctly, there could still be a lack of safety for pedestrians. In the aforementioned study, implicit and explicit cues of the approaching vehicle were altered by the conductors. This suggests that even though the vehicle would have behaved correctly/appropriately, it may have led to wrong/inappropriate/unexpected behaviours from the participants. Therefore, it appears that safety could not be ensured for all participants at all time.

VR has been used in several market research fields such as investigating shopping experiences in malls (Lee and Chung, 2008), product testing in VR (Mujber et al., 2004), and transportation research(to counter the issues of missing experience of users when encountering AVs while still ensuring safety). Several VR tools are available on the market for creating a virtual experience, including equipment such as *CAVE*[3] (Cave Automatic Virtual Environment), head-mounted display, or immersive video simulation (Dörner et al., 2013; Mihelj et al., 2013). In current literature, VR has already been used to investigate behaviours related to the communication between vehicles and pedestrians (Morrongiello et al., 2015; Chang et al., 2017; Pillai, 2017; Deb et al., 2018b). Pillai (2017) conducted a study in which participants faced an approaching AV at a zebra crossing. The study focused on implicit communication such as human-like driving behaviour, gap distance from AV to pedestrian, as well as deceleration speed. Deb et al. (2017a) developed a VR simulator in which participants were confronted with manually driven vehicles that violated traffic rules (i.e., ignored the traffic signal). These studies underline the suitability of VR for investigating user acceptance of emerging technologies, but – to the authors' best knowledge – none of them have explored in isolation the specific use case of explicit HMI for communication from AV to HRUs considering visualisation technology to display the HMI from an interaction point of view.

Nevertheless, limitations exist for methods that involve the usage of VR, including restricted field of view, resolution, and realism of the virtual environment. Therefore, research is still processing to accurately represent real-life scenarios within the virtual environment while providing a suitable testbed for pedestrian research (Deb et al., 2017a).

2.2.3 User acceptance of HMIs

Jeffries et al. (1991) investigated four techniques for user interface evaluation: heuristic evaluation, software guidelines, cognitive walkthrough and usability testing. During heuristic evaluations, user interfaces are presented to evaluators (usually specialists in the field) who are then asked to evaluate them based on their own experience. The main disadvantage of this technique is that the evaluation is biased by the mind-set of the evaluators (Nielsen and Molich, 1990). Software guidelines are published recommendations for the design of an interface so that user interface developers – not specialists – can carry out the evaluation referring to these guidelines (Jeffries et al., 1991). Cognitive walkthrough is a method, in which evaluators appraise every step necessary to perform a task and look for problems that would affect the learning by exploration (Hwang and Salvendy, 2010; Kumar, 2012; Martin and Hanington, 2012). During usability testing, the interface is studied under real-world or controlled conditions by observing users performing a set of tasks (Jeffries et al., 1991; Rubin and Chisnell, 2008; Martin and Hanington, 2012). Although usability testing is an expensive and time-consuming method when conducted in real-life, it has the advantage– in comparison with the other methods – to identify recurring and general problems (Jeffries et al., 1991). Since the AV technology is just arising and not available on the market yet,the present study focuses on these general problems rather than low-priority problems.

According to the definition of Rubin and Chisnell (2008), to be useful, a product or service must enable:

- usefulness: to which extend a product or service supports the user to reach his/her goal with regard to the willingness from the user's side to use the product or service in the first place
- efficiency: time, accuracy and degree of completion to reach the user's goal
- effectiveness: to which extent a product behaves as expected
- learnability: user's ability to operate a product or system considering a certain level of competence to operate the system after a predefined period of time
- satisfaction: user's subjective feelings, perceptions and opinions regarding satisfaction levels
- accessibility: access to the products or services that are needed to reach the goal especially for users with disabilities (e.g., temporary or permanent limited mobility)

In the context of the present study, this means that the explicit HMI should support the users' decision-making while crossing a street (usefulness) in a faster and correct way (efficiency). It should furthermore prevent wrong behaviour from pedestrians (effectiveness) without extended required competences to understand it (learnability), be perceived positively by the users (satisfaction) and be understandable for people with disabilities (accessibility) (Stadler et al., 2019).

Usability testing provides empirical data from the observation of users while using a product or system. It is advised to consider the following aspects when using the method of usability testing (based on Rubin and Chisnell, 2008):

- articulation of research questions or test objectives
- a representative amount of users (randomly or not randomly chosen)
- representation of the actual environment
- user observations during the test
- user interviews after the test
- collection of quantitative and qualitative data
- improvement recommendations for the interface.

In the present case study, conducting the test under real-life conditions raises issues related to safety. Moreover, building up a testbed in real life to test the communication from AV to HRUs would lead to great effort, as well as time and money spent. To tackle these issues, the present study proposes to use VR together with the method of usability testing to evaluate HMI concepts for the communication from AV to HRUs.

3 Method

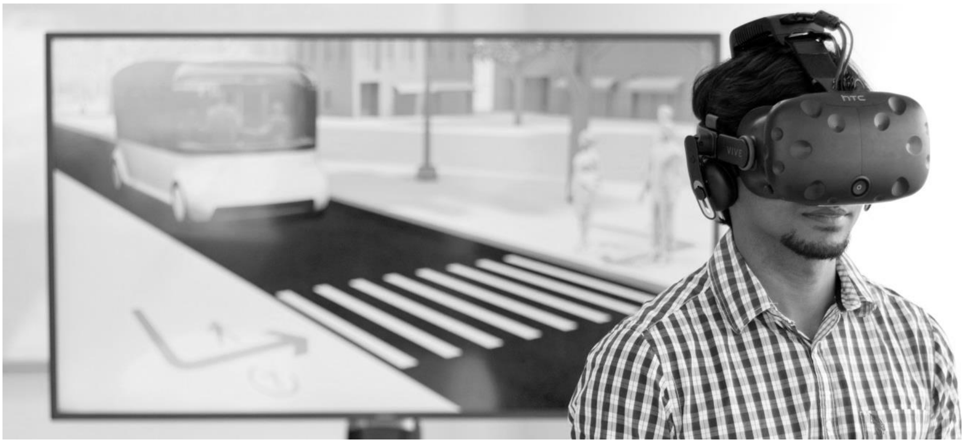
Two VR experiments were conducted in this study. The first experiment aimed to answer research question 1 'Are explicit HMIs necessary for the communication from AVs to HRUs in an ambiguous situation?'. The second experiment was conceived to answer research question 2 'Which HMI concept(s) is/are most supportive for the communication from AV to HRUs in terms of displayed information and visualisation technology for information transmission?'. Lastly, the two VR experiments provide a platform for discussion regarding the suitability of using VR for the chosen case study.

For the two VR experiments, the task for the users involved crossing a one-way street via a zebra crossing in front of an approaching AVas soon as the participants assumed the traffic situation to be safe. The task had to be repeated several times with approaching AVs that were equipped with different HMI concepts (various displayed information concepts and visualisation technologies for information transmission). A head-mounted display (HTC Vive) was used to immerse users in the virtual environment (Figure 4).

The two experiments were aligned with the methodology of usability testing as described in Sub-section 2.2.3. However, for answering the research questions, the experiments focused on three particular usability attributes as defined by Rubin and Chisnell (2008):

- Efficiency: Is the HMI supporting a faster decision-making for crossing the street?
- Effectiveness: To which extent can the HMI prevent wrong behaviour from pedestrians?
- Satisfaction: How does the user perceive the HMI for crossing the street?

Figure 4 The usage of VR for evaluating AV HMIs



The following usability attributes were not included in the present study:

- usefulness: the system must be independent from the willingness to use but provide information so that every pedestrian can use it
- learnability: no competency should be required to use the system and it should be avoided to require a learning process to use the system
- accessibility: separate tests have to be conducted for users with temporary or permanent disabilities.

The selected attributes for the study have been chosen for allowing quantitative data collection through the measurement of decision times (efficiency) and error rates (effectiveness) as well as qualitative data collection of users' subjective perceptions and preferences (satisfaction) (Table 1).

In both experiments, the decision times were defined as the duration from the moment when the participants saw the approaching AV until they started to cross the street. Regarding the error rates, participants' behaviours were noted as incorrect when they started to cross the street either when the AV executed its right of way or when the AV wanted to resume driving after stopping in front of the zebra crossing.

Table 2 Overview of data collection for the two VR experiments

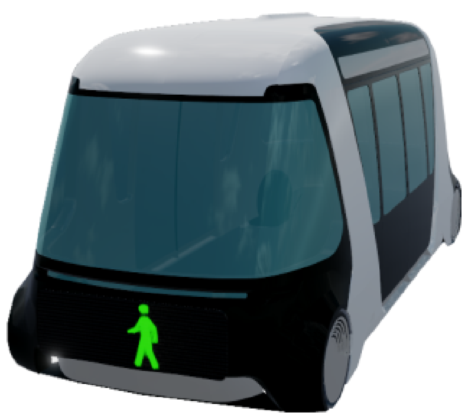
Usability attributes	*Measurement experiment 1*	*Measurement experiment 2*	*Type of data collection*
Efficiency	Decision times	Decision times	Quantitative
Effectiveness	Error rates	Error rates	Quantitative
Satisfaction	Perceived task effort	Statements about: • Visibility • Comprehensibility • Subjective support	Qualitative

For experiment 1, the perceived task effort was measured qualitatively via the NASA Task Load Index[4] (TLX) (NASA, 1986). For experiment 2, the statements related to the usability attribute satisfaction were gathered via questionnaires for evaluating the concepts' visibility, comprehensibility, and subjective support (cf. Sub-section 3.2). Compared to experiment 1, the method for qualitative data collection was changed from the NASA TLX to a questionnaire to derive more detailed information about each individual HMI concept for a subsequent comparison and ranking.

3.1 VR experimen t 1: The necessity of explicit HMIs on AVs

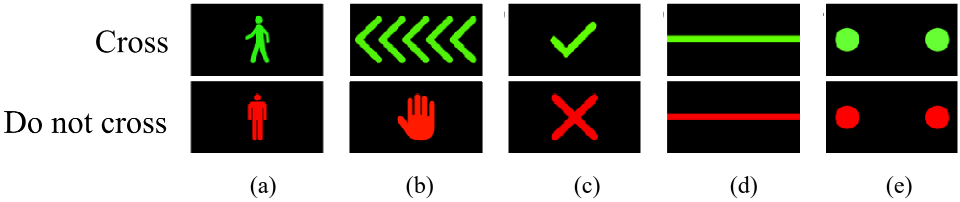
The first experiment is based on a method for data collection and evaluation within VR, as described in (Stadler et al., 2017, 2019). The objective of the first experiment was to determine the general need of explicit HMIs for the communication from AVs to HRUs in an ambiguous situation. To achieve this, the participants were placed in a virtual environment at a one-way street without traffic light and zebra crossing. The task for the participants was to cross the street once the participants assessed the situation to be safe. During the tests, the participants were approached by AVs that were equipped with various HMI concepts. Since the focus of this test was to determine the general support of HMIs, the technology to visualise the HMIs was neglected. Thus, a simple screen-like surface was put in front of the approaching vehicle that displayed the respective concept (see Figure 5).

Figure 5 AV with HMI concept (traffic light) (see online version for colours)



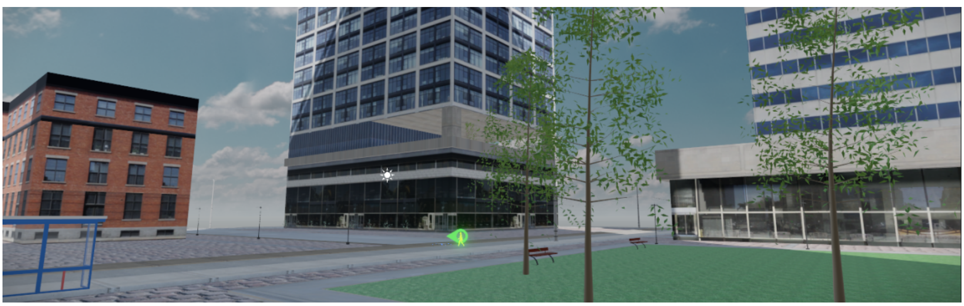
In each scenario, an AV that was equipped with an HMI concept approached the participant. The HMI concepts indicated whether it was safe for the participant to cross the street in front of the AV or not. To achieve this, each HMI concept consisted of one 'cross' variant and one 'do not cross' variant. The HMI concepts included the commonly comprehensible red and green colour combination, used at Singapore's traffic lights, in which green is used for indicating that the pedestrian has the right of way (Figure 6).

Figure 6 HMI concepts of experiment 1, (a) walking man (b) arrow (c) check (d) LED strip (e) traffic light (see online version for colours)



The virtual environment constituted an inner-city traffic scene that consisted of a one-way street with two adjoining sidewalks, several buildings, public furniture (benches, bus stops, etc.) as well as trees, street lamps and fire hydrants (see Figure 7).

Figure 7 Virtual environment of experiment 1 (see online version for colours)



Implicit information like gap distance, deceleration speed, engine sound and driving behaviour of approaching vehicles are key indicators for showing the vehicles' intentions (Pillai, 2017; Fuest et al., 2018; Song et al., 2018). Since the purpose of the experiment was to find out if specifically explicit HMI concepts can support the communication, implicit cues were neglected[5]. Therefore, the vehicles' deceleration, active driving behaviour[6], and engine sounds were neglected. The experiment followed the rules of vehicle velocity and gap distance for breaking based on Schneemann and Gohl (2016) that suggest that the HMIs must be displayed from a distance of 72.2 m when the vehicle is approaching with 50 km/h and the average time it takes to cross the one-way street is 2.7s (Stadler et al., 2019).

Since the scope of the project was following the application field of Singapore, the ethnic distribution of Singapore's population was reflected (53.8% Chinese, 10.6% Malay, 5.2% Indian, and 30.4% PRs with other ethnicities) (Department of Statistics Singapore, 2017).

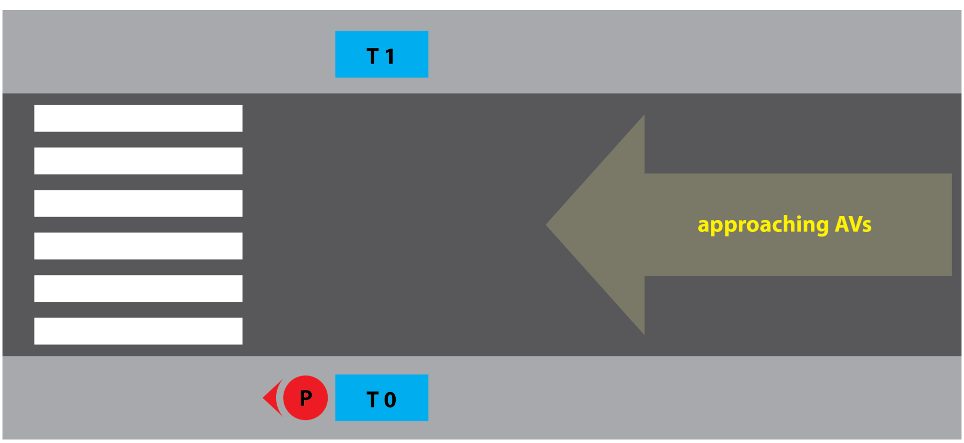
The experiment was conducted in an empty tracked area of 4.5 m x 4.5 m in which the participants were able to move freely. The first-person views as well as the movements from each participant were recorded for later analyses.

After a short tutorial to familiarise the participant with the VR environment, the experiment was conducted in which the participant had the task to cross the street when the traffic situation was assessed to be safe. After each trial the test participants had to return to the starting position. Overall twelve AVs approached (ten with equipped HMI concepts and two as a control group without HMIs). The sequence of HMI concepts was randomised to minimise the possibility of distorted results caused by the test sequence. One participant was tested at a time.

3.2 VR experiment 2: comparison of HMI concepts in consideration of display technology

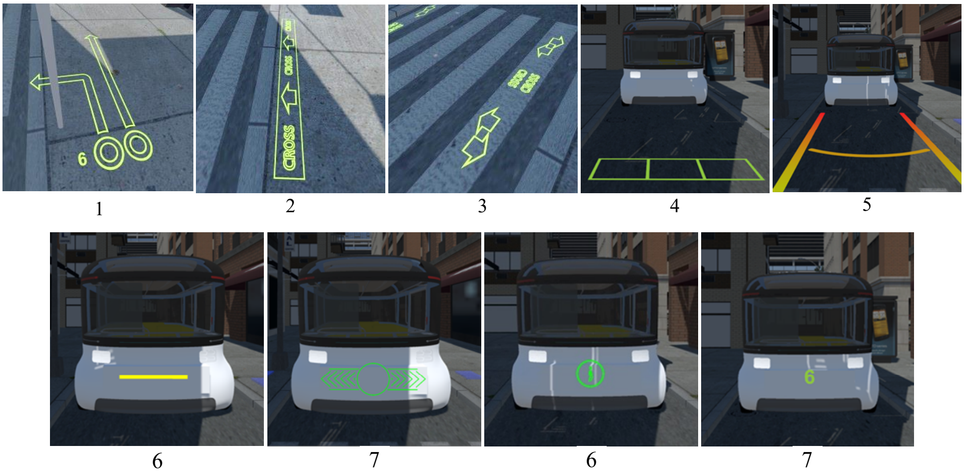
The general feedback from experiment 1 was reviewed and incorporated into experiment 2 for further improvement. This included a refined city environment as well as an adapted test scenario (see below). The main goal of the second experiment was the comparison of selected HMI concepts in consideration of used visualisation technology to transmit the information to the pedestrian. The tested technology was derived from the previously conducted benchmark analysis of HMI concepts for AVs (see Sub-section 2.1). Figure 8 shows the task scenario for the participants. In the refined scene, the participants (P) were standing at a sidewalk of a one-way street in a virtual environment. The starting point was highlighted via a blue tile on the sidewalk (T0). The task for the participants was to walk to the blue tile on the opposite side of the street (T1). To cross the street, a zebra crossing that was four meters ahead of the participants had to be used. Once the participants reached T1, the task was to go back to T0 via the zebra crossing. The participants were requested to repeat this procedure five times. Therefore, the participants crossed the street via the zebra crossing in total ten times.

Figure 8 Task scenario for experiment 2 (see online version for colours)



Every time, the participants reached the zebra crossing, an AV approached from the direction opposite to the participants' direct field of view. While the control group did not display any information, the remaining nine concepts showed HMIs with various information cues via different visualisation technologies (i.e., laser projection on street/sidewalk/zebra crossing or display-based) (see Figure 9). The zebra crossing was implemented into this scenario to avoid motivating participants to jaywalk as it was the case in experiment 1. Thus, the HMI concepts were not separated in positive or negative information as it was in experiment 1 but showed solely positive information that grants the right of way to the participant. Instead, the HMIs indicated the AVs demand to resume driving after five seconds of standing in front of the zebra crossing.

Figure 9 HMI concepts of experiment 2 (see online version for colours)



The virtual environment constituted a refined version of the environment used in experiment 1. Thus, the density of buildings, textures, lighting, urban furniture and the basic city noises were improved (see Figure 10).

Figure 10 Virtual environment of experiment 2 (see online version for colours)

In the same way as in experiment 1, the rules of vehicle velocity and gap distance for breaking were integrated into experiment 2 (see Sub-section 3.1). Since the application field of experiment 2 was Singapore, the ethnic distribution of Singapore's population was reflected (Department of Statistics Singapore, 2017).

The experiment was conducted in an empty tracked area of 5.0 m × 5.0 m, which enabled physical locomotion for participants to cover all distances in the virtual environment. The first-person view and all movements from each participant were recorded for later analyses.

One participant was tested at a time. After a short tutorial to familiarise each participant with the virtual environment, the actual experiment was conducted, in which the participant had to cross the street ten times. To minimise the risk of distorted results caused by the test order, the sequence of HMI concepts was randomised. Directly after the experiment, the questionnaire had to be filled out (i.e., rank each HMI concept comparatively). By doing this, the satisfaction level in terms of usability could be derived.

4 Results

4.1 The general necessity of explicit HMIs on AVs (experiment 1)

4.1.1 Test participants of experiment 1

The experiment was conducted with a total of 18 participants (39% female, 61% male) with an age range of 23 to 36 years (M = 27.20, S.D. = 3.54). The ethnic distribution of all participants was as follows: 10 Chinese, 2 Malay, 1 Indian, and 5 participants with other ethnicities. No differences in results were measured due to thedemographic backgrounds of the participants.

4.1.2 Quantitative results of experiment 1: decision times and error rates

To quantitatively answer the first research question(i.e., determine the general needfor explicit HMI concepts on AVs), the average decision times and average error rates from the control group were compared withthe participant performances involving the aggregated HMI concepts (see Figure 11 and Figure 12).

Figure 11 Comparison of average decision times of experiment 1

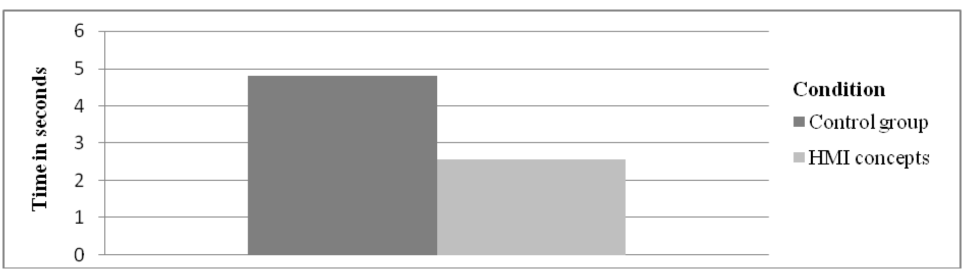


Figure 11 shows that the aggregated average decision time from the control group to the aggregated average of all HMI concepts decreased from 4.8 seconds to 2.5 seconds which equals a decrease of 48%. This proves that the HMI concepts improve the usability attribute of efficiency.

Figure 12 Comparison of average error rates of experiment 1

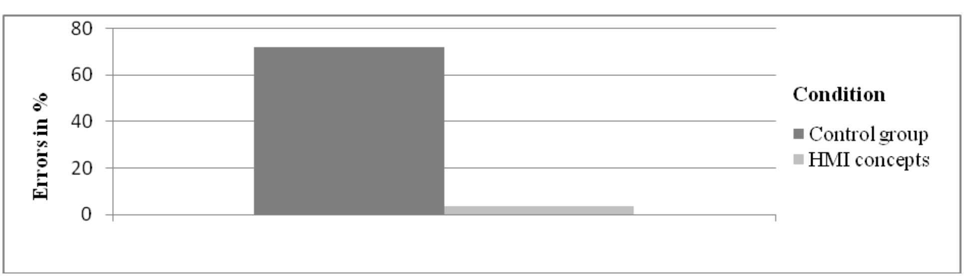


Figure 12 shows that the aggregated average of all HMI concepts generally reduced the error rates. In 72.2% of all tests with the control group, errors were measured. In contrast, only in 3.3% of all tests with AVs that were equipped with explicit HMI concepts, errors occurred. The results show that the HMI concepts decreased errors by 68.9%. This proves that with explicit HMIs, the usability attribute of effectiveness is improved.

4.1.3 Qualitative results from experiment 1: perceived task effort

In reference to the TLX procedure (described in 3.1), a more negative value indicates that the participant perceives the task as requiring less effort (see Figure 13).

Figure 13 Average perceived effort (TLX) of experiment 1

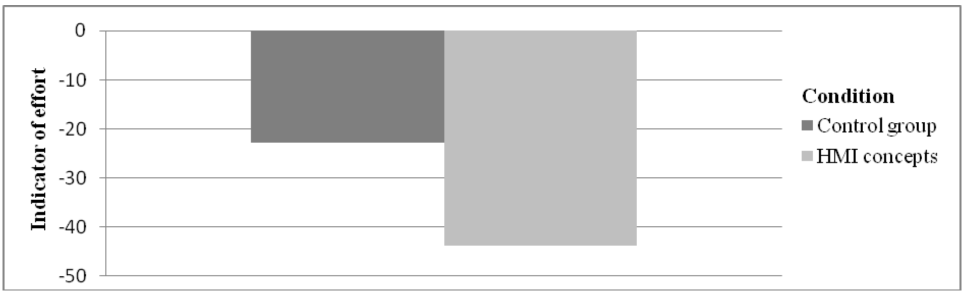


Figure 13 shows that the subjective efforts had an indication value of –22.8 when participants were confronted with the control group. In contrast, the indication value decreased to –43.7 when the approaching AVs were equipped with any of the explicit HMI concepts (the measures of all tested HMI concepts were aggregated). Thus, the perceived effort for crossing the street decreased by 47.8% when the AVs were equipped with explicit HMI concepts.

4.2 Comparison of HMI concepts in consideration of display technology (experiment 2)

4.2.1 Test participants of experiment 2

Following the same basic requirements as for experiment 1 (see 4.1.1), 19 participants (37% female, 63% male)with a range of 23 to 34 years (M = 26.80, S.D. = 2.78) have been recruited for the experiment (based on Rubin and Chisnell, 2008). The ethnic distribution of all participants was as follows: seven Chinese, two Malay, three Indian, and seven participants with other ethnicities. No differences in results were measured due to the demographic backgrounds of the participants.

4.2.2 Quantitative results from experiment 2: decision time and error rates

To quantitatively answer the second research question (which HMI concept(s) is/are the most usable one(s) in consideration of display technology), the participants' average decision times of each individual HMI concept were collected for a subsequent comparison (see Figure 14).

Figure 14 Comparison of average decision times of experiment 2

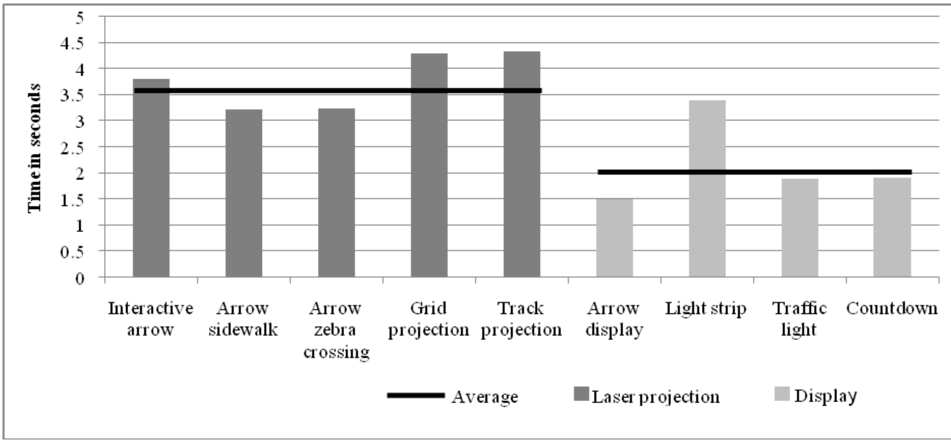
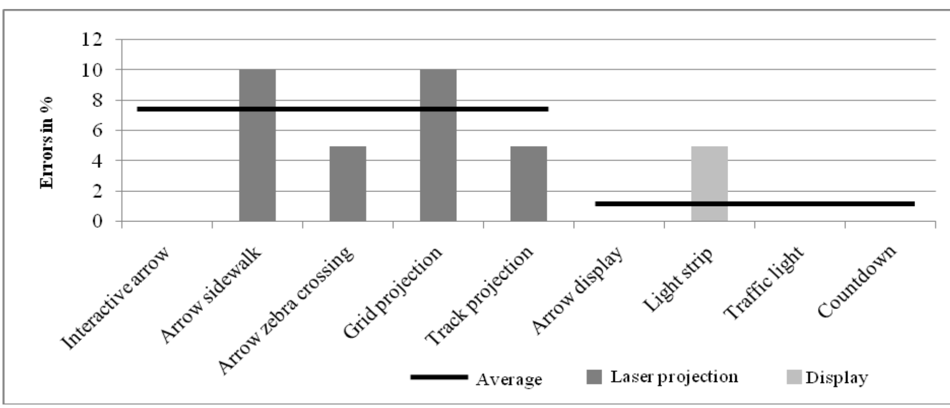


Figure 14 shows the participants' average decision times of each individual HMI concept. The graphs show that the display-based concepts, and especially the 'arrow display' concept, resulted in the least decision times needed to start crossing the street. While the decision times of the display-based concepts ranged from 1.5 seconds to 1.9 seconds (with the exception of the concept 'light strip' that resulted in longer decision times for the participants), all projection-based concepts had average decision times between 3.2 seconds and 4.3 seconds.

Figure 15 Comparison of average error rates for experiment 2



Subsequently, the participants' average error rates foreach individual HMI concept were collected to compare the usability attribute of effectiveness (see Figure 15).

Figure 15 shows that the display-based concepts led to safer behaviour and thus, resulted in better performances from participants' side. While in four out of the five projection-based concepts errors occurred, only in one out of the four display-based concepts a wrong behaviour was observed.

4.2.3 Qualitative results from experiment 2

As a last step, qualitative data was collected for allowing a comparison of all tested HMI concepts. For each HMI concept, there were three questions to answer:

Q1 Did you immediately see the HMI concept?

Q2 Could you immediately interpret the HMI concept correctly?

Q3 Did you find the HMI concept supportive?

The HMI concepts in Figure 16 are abbreviated as follows:

C1 Interactive arrow

C2 Arrow sidewalk

C3 Arrow zebra crossing

C4 Grid projection

C5 Track projection

C6 Arrow display

C7 Light strip

C8 Traffic light

C9 Countdown

Figure 16 Subjective comparison of HMI concepts of experiment 2

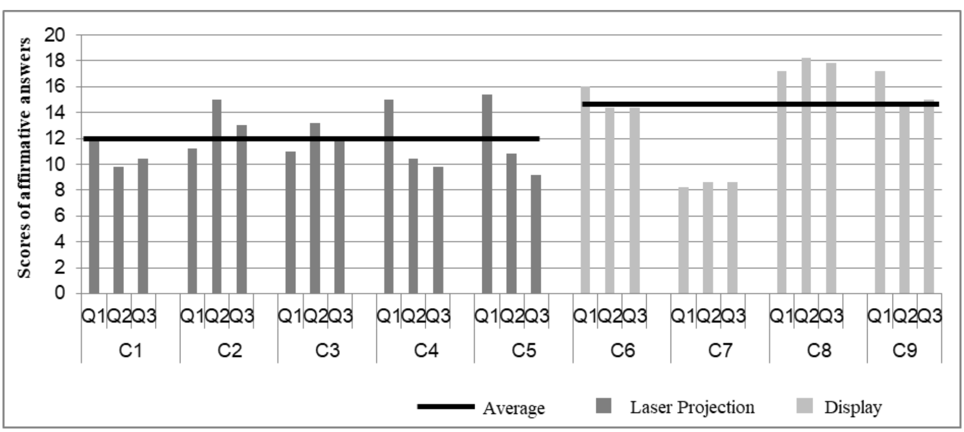


Figure 16 shows that the display-based HMI concepts (C6 to C9) were easier to see, to interpret, and were also more supportive than the projection-based HMI concepts (C1 to C5). Similar to the quantitative results of experiment 2 (see 4.2.2), the concept 'light strip' (C7) was perceived as less visible, less interpretable, and less supportive for crossing the street than the other display-based HMI concepts. The concept 'traffic light' (C8) was perceived as the most visible, most comprehensible, and most supportive concept in the qualitative data analysis.

5 Discussion

5.1 About the general necessity of explicit HMIs on AVs (RQ 1)

The first research question thematised whether explicit HMI concepts have the capability to generally improve usability in the communication between pedestrians and AVs in ambiguous situations. These findings were derived via a quantitative and qualitative data collection through decision time measurements, error rate measurements, and a NASA TLX test for understanding perceived effort to achieve a task. The results showed that the decision times decreased by 48% and that error rates dropped by 68.9%. Furthermore, the TLX test revealed that the subjective effort to cross the street decreased by 47.8% when the approaching AVs were equipped with explicit HMI concepts. Therefore, the results of experiment 1 showed that explicit HMI concepts generally improved the usability factors efficiency, effectiveness, and satisfaction in the chosen case study.

The communication from AVs to HRUs has already been investigated in several published studies. The studies result in two major directions of findings. While some investigations conclude that explicit HMIs improve the communication from AVs to HRUs (Bikeleague, 2014; Lagström and Lundgren, 2015; Färber, 2016; Müller et al., 2016; Matthews and Chowdhary, 2017; Pillai, 2017; Deb et al., 2018b; Mahadevan, 2018; Song et al., 2018), other investigations argue that implicit communication cues are sufficient and thus, explicit HMIs are not necessary (Clamann et al., 2015; Rothenbücher et al., 2016; Dey and Terken, 2017; Millard-Ball, 2018).

Rothenbücher et al. (2016) concluded after a Wizard-of-Oz experiment on a university campus that the participants were "surprisingly capable of managing this breach of normality without any communication cues. […] this is because pedestrians and cyclists have extensive experience in manoeuvring without such signals at night-time and in other situations when the driver can't be seen.". However, the study was conducted at two locations at a university campus and thus, the traffic scenarios were simplified. Additionally, the chosen traffic locations entailed slow vehicle speeds since one study was conducted at a pedestrian crossing in front of a main street (the AV approached from a parking space) and secondly at a roundabout. The researchers state further limitations such as participant biases and the absence of any passengers in the AV since this might have influenced their decision making and behaviour. Millard-Ball (2018) also considered explicit HMIs as not necessary. He used game theory to analyse the interactions between AVs and HRUs at crosswalks and concludes that pedestrians will be able to behave with impunity since the AVs are programmed to behave risk-averse. Furthermore, Clamann et al. (2015) found no "significant differences between the displays, which means they were as effective as the current status quo of having no display at all".

Nevertheless, there are several investigations that show opposing results. Deb et al. (2018a) wrote in consideration of the investigation by Clamann et al. (2015): "The car was driven by a driver, although the participants were instructed that it was running in autonomous mode. Having a human in the driver seat in front of the steering wheel is not a scenario that is appropriate for studying AVs" (referring to the Wizard-of-Oz method). In contrast to the previously mentioned studies, there are several studies that conclude that explicit cues are supportive for the communication between AVs and pedestrians in ambiguous situations. Even though the investigation from Pillai (2017) exclusively focused on implicit communication between AVs and HRUs, it was concluded that visual cues (explicit HMIs) would support implicit communication especially in case of bad weather conditions. In a similar context, Lagström and Lundgren (2015) concluded that their prototype of explicit communication (i.e., an LED strip) helped pedestrians to understand the AV's intentions and helped to decrease the crossing time for pedestrians. Deb et al. (2018b) conducted experiments in virtual environments to investigate the impact of external HMIs on crossing behaviours of pedestrians in which they concluded that external HMIs improved the communication between AVs and HRUs. Similar to the study from Deb at al. (2018b), the present study revealed that external interfaces on AVs are necessary to ensure effective communication between AVs and pedestrians since decision times and errors are reduced and satisfaction levels are increased. Chang et al. (2017) conducted a VR experiment in which participants encountered AVs with moving headlights that imitated eyes and thus function as explicit cues. The authors concluded that the concept let participants cross the street quicker and safer. Johannsen (2009) confirmed the aforementioned results in his general theoretical investigation of HMIs: "High levels of safety, performance, and efficiency have been achieved by means of the increased use of automatic control. Interestingly enough […] the need for improved human-machine communication increased (rather than decreased) with the increased degree of automation".

The results of the present study underline the need for explicit HMIs. However, since there is still no consensus about this question, further research has to be conducted. Rasouli and Tsotsos (2017) concluded: "The number of these studies, however, is still relatively small, compared to classical studies. […] This means more studies of similar nature to classical studies have to be conducted involving autonomous vehicles".

5.2 About the comparison of HMI concepts in consideration of display technology (RQ 2)

The second research question was: 'Which displayed information and technology of HMIs are most supportive for the communication from AV to HRUs?'. To answer this question, a second experiment was conducted with quantitative and qualitative data collection through decision time measurement, error analysis, and a questionnaire. The quantitative results show that display-based concepts decreased the decision times and error rates more than projection-based concepts. The qualitative data collection corroborated this, since the three concepts with the best results were display-based. Thus, the concepts 'arrow display', 'traffic light', and 'countdown' are the overall most usable explicit HMI concepts of the tested selection.

Current research tends to take technologies such as projections, displays, LED strips, and robotic hardware into account when investigating the impact of explicit cues in the context of AV to pedestrian communication (Dey and Terken, 2017; Zimmermann and Wettach, 2017; Deb et al., 2018b; Mahadevan, 2018). Deb et al. (2018b) investigated several display-based explicit HMI concepts like a green blinking text 'braking', an animated walking silhouette, as well as a 'SMILE' indication. The concepts have partially been enhanced with verbal messages. The authors conclude that the animated walking silhouette is a very common and comfortable symbol for pedestrians. This is consistent with the findings of the present study since the 'traffic light' concept (which is similar to the animated walking silhouette):

1 was among the most usable concepts regarding the attributes effectiveness and efficiency

2 achieved the highest scores for visibility, comprehensibility, and subjective support for crossing the street (which accounts for the usability attribute satisfaction).

Charisi et al. (2017) focused on the comprehensibility of symbols and colours of children rather than the technology for displaying it. Their survey substantiated the fact that the children could decode traffic light symbols, walking figures, stop signs, and a ‘child-walk\[7] signals the easiest. Projection-based symbols (e.g., a projected zebra crossing) were included in the survey as well. The results show that children decoded projected information noticeably worse than display-based information (Charisi et al., 2017). Similar to their conclusion, it was observed in the present study that display-based HMI concepts decreased decision times, and error rates more than projection-based HMI concepts. Furthermore, within the qualitative analysis, the present study proved that projection-based information is less visible, comprehensible, and supportive than display-based HMI concepts. It is anticipated that one key fact for this is the detachment of information from the AVs. This means that the information that was displayed on the sidewalk or zebra crossing via the laser projection could not be re-connected to the approaching AV by the participants.

By answering the second research question, it became visible that display-based HMI concepts and especially the concepts ‘arrow display’, ‘traffic light’, and ‘countdown’ resulted in the best performances and satisfaction levels of participants. Compared to related published literature, the presented study evaluated HMI concepts in an immersive authentic traffic scenario involving AVs. In this way, beyond subjective preferences of users, actual behaviours and performances could be measured and therefore, the impact on performance could be evaluated not only qualitatively but also quantitatively. In further studies, it will be investigated to which extent pedestrians would solely rely on the laser projection even though it is detached from the AV.

5.3 About the suitability of VR for conducting usability tests for the chosen case study

The two VR experiments provide a platform for discussing the suitability of using VR for the chosen case study. The most important aspect in this context is safety. The present study, the researchers conducted usability tests that enabled experiences of the new technology but with ensured safety for participants and equipment at all time. Deb et al. (2017a) concluded: “The use of a simulator for pedestrian research has many benefits over real-world studies. The most important benefit is safety – a virtual environment displayed in a lab clear of obstacles provides a minimal level of risk to the participant”.

The second aspect is the validity of using VR in the chosen case. Rothenbücher et al. (2016) conclude that Wizard-of-Oz principles are more advantageous than VR-based methods since Wizard-of-Oz allows “[…] *in situ* observation of behavior in a natural environment, rather than a lab”. In contrast to Rothenbücher’s statement, there are several studies that prove the advantages of using VR in pedestrian safety research (especially involving AVs) (Deb et al., 2017a; Pillai, 2017; Zimmermann and Wettach, 2017). Deb et al. (2018a) stated: “Having a human in the driver seat in front of the steering wheel is not a scenario that is appropriate for studying AVs”. Within another study, Deb et al. (2018b) wrote: “However, participants’ exposures in a traffic environment with the threat of being hit by a vehicle may change their perceptions to a great extent. […] a picture or video-based survey cannot create that threat". The mentioned study was conducted on the basis of a simulator that has already been validated by Deb et al. (2017a). The authors conclude after the experiment: "Based on this study, it appears that participants will respond to traffic in a simulator as they would in the real world; they look for the vehicle before crossing and wait for the vehicle to stop. […] Overall, it can be said that this VR setting works well and can be a valuable mode for similar research involving FAVs[8] and road users, especially pedestrians" (Deb et al., 2018b).

A further advantage of using VR is costs. Pillai (2017) states that compared to Wizard-of-Oz approaches, using VR is cheaper. Deb et al. (2017a) also state that the VR equipment is within a price range so that almost any lab could afford such equipment and work with VR. Within the present study, these statements could be confirmed since the costs of the used VR equipment (including high-performance computer and HMD) was still more cost-effective compared to purchasing hardware and equipment for the conduct of Wizard-of-Oz experiments.

As a last aspect, using VR in the present study constituted a fast way to test pedestrian behaviour in a laboratorial environment with high flexibility in adapting parameters. Furthermore, due to the fact that the equipment is mobile, there was the possibility to conduct the tests in different locations. Regarding flexibility of using VR, Deb et al. (2017a) wrote: "The time needed to reset for the next trial or participant is minimal bordering on non-existent, which allows a great number of trials and participants to be run in a relatively short amount of time".

5.4 Contribution

One contribution of the present study is determining the suitability of using VR for behavioural research(e.g., within market research involving AVs and pedestrians). The investigation showed that the usage of VR benefits safety for participants, provides valid results, is a cost- and time-effective alternative to experiments in real-life conditions, and provides a laboratorial environment that let all participants face exactly the same conditions. VR turned out to be a valid research tool to investigate requirements for upcoming markets like in this context autonomous mobility. Furthermore, the study contributes to the theoretical usage of VR in research.

Secondly, the present study contributes to the definition, regulation, and development of autonomous mobility in the way that it showcased the general need for explicit HMIs to provide information to pedestrians in ambiguous situations. This was proven by the conduct of two usability tests that quantitatively and qualitatively evaluated behaviours and preferences of participants when being exposed to AVs. Additionally, a first ranking of HMI concepts including visualisation technology (i.e., displays and laser projections)were presented for further consideration for the development of AVs by car manufacturers as well as for defining regulations for this technology by governments. A key fact for using VR in this context was the possibility, to neglect other explicit or implicit communication cues like sound, deceleration, and lateral steering. Thus, the visual HMI concepts could be evaluated in an isolated way and under laboratorial conditions.

5.5 Limitations and further work

The present study showed limitations as well. Since the conductors wanted to ensure that the participants' behaviour at the zebra crossing is exclusively triggered andinfluenced by the approaching AV, other vehicles as well as other pedestrians (i.e., agents) were neglected from the study. In subsequent interviews, several participants pointed out that this fact took them away from presence in VR.

In total, data from 37 participants was collected. Since the chosen application field for the case study is Singapore, the number of participants does not represent a statistical quota sample of Singapore's population. However, Rubin and Chisnell (2008) stated in this context that research indicates that testing four to five participants of each type would be sufficient to expose the vast majority of usability problems and suggested that a small amount of participants already have the capability of identifying the most relevant usability problems. Nevertheless, it is planned to increase the number of participants in upcoming experiments.

The authors focused specifically on the usability of interaction between pedestrians and AVs in an ambiguous situation. Therefore, two main influences were neglected within the study:

i) the consideration of weather- and light-conditions, and ii) the implementation of technical properties for the visualisation technology. Since it is anticipated that these factors have a key impact on the visibility of HMIs, weather-simulations as well as enhanced display properties for chosen technologies are planned to be implemented in future studies.

Lastly, the focus of this study was to evaluate the usability attributes efficiency, effectiveness, and satisfaction in order to identify the general need for explicit HMI concepts as well as a selection of usable concepts. In future experiments, additional usability attributes like accessibility will be considered since it is a fundamental influence on the usability especially for people with disabilities.

6 Conclusions

Technological advances in the business of automated transportation are not only connected to advantages but also raise challenges and questions. These challenges have to be addressed for a successful market entry since without ensured user acceptance, the future deployment of AVs remains unpredictable regarding market acceptance. Safety has to be ensured especially for vulnerable road users like pedestrians and cyclists. The present study showed that explicit HMIs improve the usability in term of efficiency, effectiveness, and satisfaction during the interaction between AVs and pedestrians in an ambiguous situation. Furthermore, a comparison of concepts in consideration of used visualisation technology made clear that display-based HMIs were more effective, efficient, and satisfactory for the participants in comparison with laser projections. The display-based concepts 'arrow display', 'traffic light', and 'countdown' achieved the highest scores in the quantitative and qualitative analysis. Even though the present study focused on the underlying research of the interaction between AVs and pedestrians, the outcome results in a useful recommendation for businesses in order to prepare a successful market entry. For the present study, the usage of VR constituted a safe, low-cost, and flexible alternative that enabled a high throughput of participants in a short period of time and enabled data collection in a laboratorial environment. Thus, disruptive factors like temperature differences and sounds could be neglected. Additionally, it was possible to confront each participant with identical scenarios and conditions. The following improvements will be implemented for further studies: Firstly, the virtual environment will be enhanced with weather, traffic, and pedestrians simulations to increase realism. Moreover, since implicit cues like deceleration speed and gap distance to the participants constitute key indicators for a successful communication between AVs and pedestrians, active driving behaviour that transmit simplicit communication will be included in future experiments. Lastly, the usability attribute of accessibility will be considered in upcoming experiments.

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Notes

1 In this paper, the term AV refers to level 5 autonomous vehicles as defined by (SAE International, 2016).

2 Explicit communication transmits the message in a direct way (e.g., a sign that shows 'STOP'). In contrast, implicit communication transmits the message indirectly (e.g., by decelerating) (Dey and Terken, 2017; Fuest et al., 2018).

3 CAVE is hardware that allows VR experiences through a room whose walls, ceiling, and floor surround the user with projections (Cruz-Neira et al., 1992).

4 "The NASA Task Load Index is a multi-dimensional rating procedure that provides an overall workload score based on a weighted average of ratings on six subscales: mental demands, physical demands, temporal demands, own performance, effort, and frustration" (NASA, 1986).

5 In contrast to an experiment that is conducted in real-life conditions, with the help of VR, implicit cues could be neglected to test the impact on behaviour caused by the explicit HMI concepts in isolation.

6 Active driving behaviour in this context refers to driving behaviour that actively shows the vehicle's intentions. One example for this is lateral steering of the vehicle to the middle of the lane to show the intention to execute its right of way.

7 The 'child-walk' signal constitutes is a graphical illustration of a comic figure that holds a sign that can provide either positive or negative information (i.e., walk or don't walk) (Charisi et al., 2017).

8 Deb et al. (2017b) use the abbreviation FAV for 'fully autonomous vehicle'. This equals a level 5 AV (SAE International, 2016).