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Easy to handle: Exploring users' interactions with an augmented reality human-machine interface for virtual stops in automated on-demand mobility scenarios

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ABSTRACT

For the success of future shared automated mobility on-demand (SAMOD) a high quality of service needs to be assured. One key challenge lies in the passenger journey, particularly in finding the designated virtual stop (vStop) for pick-up and identifying the approaching shuttle. Therefore, the new vStop human-machine interface (vStop HMI) concept supports passengers with means of augmented reality (AR). This explorative user study with young adults ($N = 44$) used a virtual reality (VR) setup to simulate the AR-based vStop HMI and answers two research questions across two consecutive scenarios: (1) When using an AR-based navigation aid like the vStop HMI, users tend to focus heavily on their device while walking, which may increase the risk of negligent roadside behavior. While restricting AR information access during walking might reduce this risk, how does it affect overall user experience? To examine this, we compared a vStop HMI with restricted AR information access against a baseline condition. Results showed positive effects on user experience and acceptance for both HMI versions, although workload was partly negatively affected. (2) When identifying the approaching shuttle, does using the vStop HMI effectively assist users in doing so and lead to positive user experience? Usability testing indicated positive rates of workload, user experience, and acceptance during the shuttle identification task. Overall, the findings suggest that selectively restricting AR information during navigation tasks can help mitigate undesired user behavior in roadside environments while maintaining high levels of pragmatic quality and acceptance. Moreover, the vStop HMI enables seamless shuttle identification, even under complex conditions. By improving these critical stages of the passenger journey, the vStop HMI concept has the potential to enhance the overall quality of SAMOD services and increase public acceptance of future shared, automated, demand-responsive transportation systems.

1. Introduction

Latest technological developments have sparked a new era of urban transportation, characterized by the combination of demand-responsive transportation systems and highly automated vehicles (HAVs, SAE level 4) (SAE International, 2021). These systems offer on-demand rides in shared automated vehicles (SAV), which customers can book via smartphone applications and board at flexible pick-up locations, also referred to as virtual stops (vStops), located nearby (Tcheumadjeu and Rummel, 2024). In shared/pooled ride operation, and synchronized with public transportation, these services could potentially scale up and bring significant benefits to future mobility systems (Hyland and Mahmassani, 2020). The benefits are manifold: shared automated mobility on-demand (SAMOD) systems promise, e.g., increased efficiency and reduced resource consumption (Garus et al., 2024). They also could improve the service quality of mobility for a wide range of user groups, since use cases range from last-mile solutions that complement public transportation to free-floating services in specific deployment areas (Riener et al., 2020; Nahmias-Biran et al., 2020). Various pilot projects in research contexts and the first commercial operation by Waymo and Cruise have demonstrated technical feasibility (Hisham et al., 2024). However, sustainable and long-term operation remains uncertain (Carreyre et al., 2024). Here, among other factors like regulations, technological developments, and economic considerations,

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overall user acceptance is likely to play an important role in actual user adoption (Greifenstein, 2024). Therefore, the user experience (UX) across the entire user journey of these new SAMOD services must be addressed in design, research, and development. Consequently, this includes all steps before and after the actual ride in the vehicle, such as finding the flexible pick-up location and seamlessly identifying the correct SAV (Hub et al., 2023). Furthermore, interaction with an information system of the mobility service provider and the mobile device should also be helpful, easy to use and accepted by users. Therefore, this paper investigates the new concept of human-machine interface for virtual stops (vStop HMI) in two user journey scenarios in an explorative user study. The main aim of the vStop HMI, which utilizes means of augmented reality (AR), is to guide the user to get to the flexible pick-up location and assist in identifying the booked SAV.

Not finding the flexible pick-up location, which lacks real-world cues, and/or failing to recognize the correct shuttle instantly can cause delay, stress, and frustration for users. Circumstances such as unfamiliar territory, time pressure, and large, complex traffic hubs (e.g., airports or central train stations) could make this even more difficult for SAMOD customers. Consequently, such delays may disrupt pooled ride operations and reduce UX for all passengers alike (Kucharski et al., 2021). Previous research revealed that when getting to vStops, an AR-based HMI can support users by presenting information efficiently (Hub et al., 2023; Hub and Oehl, 2022). Utilizing AR, the vStop HMI enriches the physical environment with digital information regarding the presence and exact location of the vStop. However, when navigating to a vStop following the AR-HMI, a previous field study provided evidence that users were highly focused on the video-see-through AR screen of the device (Hub and Oehl, 2022). Reasons for this could be varied, including cognitive tunneling or novelty effects (Elford et al., 2022; Koch et al., 2018). Consequently, while the vStop HMI should be helpful for finding the flexible pick-up location, safety concerns and negligent behavior walking must be avoided (Frej et al., 2022). Hence, the first aim of this research revolves around how the AR information presentation to the users could be restricted while walking, and how this affects the UX of the vStop HMI. Even in pedestrian navigation with AR, this aspect has not yet been investigated.

For the scenario of shuttle identification, the vStop HMI, and particularly its use of AR, is expected to be helpful. By highlighting the SAV directly in the user's field of view, the vStop HMI could reduce uncertainty and support timely boarding. This may be especially beneficial in complex situations with many identical-looking shuttles at the same pick-up location (e.g., traffic hubs, airport, train station). Here, the use of an AR HMI could provide high pragmatic quality to users (Hub et al., 2023; Rongen et al., 2022; Vallet et al., 2020). In contrast, conventional interfaces typically present information such as a picture of the vehicle and its license plate, which appears insufficient in more complex settings (Hub et al., 2023). Hence, the second aim of this research is to evaluate the vStop HMI regarding UX in shuttle identification tasks, which has not yet been investigated, too.

In essence, this research paper presents a prototypical concept for a vStop HMI that helps users to navigate to a vStop and to identify the correct shuttle. The aim of this work is to evaluate whether the vStop HMI can enhance the UX of SAMOD customers in two consecutive user journey scenarios to ultimately promote new forms of shared automated mobility services. The vStop HMI prototype is therefore expected to achieve high pragmatic quality (to demonstrate its usefulness), high acceptance (to indicate potential for user adoption in the future), and low workload (to signal ease of use).

Results indicate positive outcomes for both HMI variants. No negative effect on user experience or acceptance was found when restricting AR information presentation on the vStop HMI while walking, although workload (i.e., frustration) was partly negatively affected. However, despite positive evaluation, participants verbally expressed their disliking of the information restriction method. In the shuttle identification scenario, the vStop HMI was evaluated very positively across all metrics. As a result, this investigation highlights the assistive character of the vStop HMI and AR technology in the context of SAMOD.

This research contributes to the user-centered design of a vStop HMI as well as to the broader research fields of SAMOD and mobile AR. Furthermore, it advances the research for valuable use cases for AR applications in traffic and mobility environments. Finally, the results indicate the positive impact of a vStop HMI for SAMOD uses cases, suggesting that such new and sustainable transportation solutions could achieve market success.

1.1. *Future automated demand-responsive transportation and the vStop HMI*

Developments in the field of HAVs have been steady. Emerging trends in the transportation sector, like automated demand responsive transportation and shared automated mobility on-demand (SAMOD), seek to improve efficiency and effectiveness of urban and rural transportation (Wang and Yang, 2019; Chen et al., 2021; Garus et al., 2024). In future SAMOD operation, algorithms determine the matching between riders and shared automated vehicles (SAVs, sometimes referred to as automated shuttle buses; ASBs) and routing to balance vehicle capacity and travel times (Ke et al., 2021). The concept is based on the idea that individuals share rides to their destinations. In combination with conventional public transportation, such services could further increase resource efficiency by simultaneously meeting increased demand (Sieber et al., 2020). In predefined areas of deployment, the number of vehicles on the road could be reduced, miles traveled per vehicle could be increased, and user travel times could be reduced (Garus et al., 2024; Paparella et al., 2024).

From the user perspective, trips are booked via mobility service provider apps, just like today with present operators like Uber, Bolt or Grab. The user journey also resembles that of conventional ride-pooling services, since stop-based pooling is applied (Harmann et al., 2022; Zwick and Axhausen, 2020). However, due to the fact that the service is operated with SAVs, the pick-up scenario will differ from today's services significantly because maneuvering an SAV requires coordination and planning at the local level (Hub et al., 2023). In these situations, the comprehensive concept of virtual stops functions as a form of virtual traffic infrastructure. Here, the actors and infrastructure elements in the local traffic space are connected to enable coordinated maneuvers (Hub et al., 2023). In that regard, the vStop HMI brings relevant information to the users to give guidance and to reduce uncertainty and stress, dependent on the scenario. Recent concepts and prototypes of the vStop HMI not only mark the vStop location but also guide users to the pick-up point. It has been shown that UX, acceptance, and workload during use indicate substantial value for users (Hub and Oehl, 2022). This work focuses on investigating a vStop HMI prototype in the SAMOD user journey scenarios of finding the vStop and identifying the shuttle. In doing so, it provides another step towards the user-centered design of a vStop HMI for future SAMOD.

1.2. *Mobile augmented reality*

Augmented Reality (AR) is an immersive experience of human-computer interaction that adds digital content to the real world. Azuma (1997) described it as a system with three basic features: the combination of real and virtual worlds, real-time interaction, and accurate 3D registration of virtual and real objects. The content can span multiple sensory modalities, including visual, auditory, and haptic feedback (Billinghurst et al., 2015).

Visual AR works by overlaying digital information onto the real world, for example through a screen. Technically, this is achieved by a computational process of sensing, modeling, enhancing, and displaying (Siriwardhana et al., 2021; Chatzopoulos et al., 2017). Sensing involves using a device to capture data from the physical world. The device then processes this sensory information to obtain a model of the world.

Subsequently, the AR system enhances this model by adding digital objects (usually drawn from a cloud server). Finally, the device displays this enhanced model to the user via the user interface. Accordingly, the strength of AR lies in its ability to make users more aware of information relevant to their interaction with the real world (Nee and Ong, 2023). Initially, AR was only used stationary due to the required computing power (Billinghurst et al., 2015). Today, smartphones and tablets allow for mobile use of video-see-through AR (e.g., from Apple, Google, or Samsung) (Chatzopoulos et al., 2017; Choi et al., 2024). Besides these hand-held devices, wearables like smart glasses and AR headsets, often referred to as head-mounted displays (HMDs) (e.g., HoloLens, Meta2, Apple Vision Pro) are also prominent mobile AR devices (Waisberg et al., 2024; Siriwardhana et al., 2021; Vertucci et al., 2023). However, this work focuses on smartphone AR, which shows high potential for the given scenarios due to its reliability, performance, and portability, and which has also been the subject of previous vStop HMI research (Choi et al., 2019; Hub and Oehl, 2022).

In general, AR technology is a rapidly evolving field and has found applications in a wide range of industries and use cases, including marketing, medicine, education, and entertainment (Dey et al., 2018; Chatzopoulos et al., 2017; Vertucci et al., 2023). AR has also been applied to pedestrian navigation and seems to offer a more immersive experience compared to maps navigation, especially in unfamiliar environments (Bhorkar, 2017; Brata and Liang, 2020; Dong et al., 2021). Commercially available examples come from Apple (AR feature in Apple Maps) and Google (Live View function in Google Maps) which use the live camera view of the street in front of the user, overlay directions with arrows and information, and give instructions (Gallagher, 2021; Hall, 2023).

1.3. Research questions

The underlying explorative objective of this research is to gain systematic insights into the usefulness of a proposed vStop HMI prototype in two consecutive SAMOD user journey scenarios. Two core aspects of HMI utilization are addressed. In the first user journey scenario of navigating to a flexible pick-up location, a previously investigated vStop HMI AR design proved intuitive to use, characterized by high pragmatic quality, high acceptance, and low cognitive workload ratings. However, in the naturalistic field study, researchers observed that participants were very consumed by the AR information presented on the mobile device (Hub and Oehl, 2022). As a current phenomenon, some commercially available AR pedestrian navigation applications advise careful behavior, suggesting that users stand still while retrieving information. For example, Android systems notify users and black out the display if the phone is continuously held up while walking. Apple's AR Live View issues a warning saying "For your safety, keep your phone down while you walk" (Hall, 2023). Based on this current phenomenon and the observed user behavior, this study compared a baseline vStop HMI to a variant with restricted AR information presentation in order to examine whether such a safety feature affects key user experience dimensions. Hence, the goal is gaining insights whether restricting AR information during walking can be justified:

RQ1: Compared to a baseline variant, how does restricting the AR information during walking affect UX, acceptance, and cognitive workload ratings of the vStop HMI?

As for the shuttle identification scenario, a very first vStop HMI design proposal has been made in previous work (Hub and Oehl, 2022). However, a comprehensive user study evaluation of the vStop HMI prototype, especially investigating the use of AR technology in that particular task, has not been conducted yet. Conventional approaches to shuttle identification, such as number plates or service-specific chassis markings, may be sufficient in simple, low-density traffic contexts. However, in more complex environments, e.g., with multiple identical or similar-looking vehicles arriving simultaneously, such static markings are difficult for users to perceive and interpret quickly, which can induce uncertainty and stress. For this reason, the use of AR appears to be a user-centered alternative, as it enables dynamic highlighting of relevant objects in near-vicinity conditions (e.g., precisely referencing the correct shuttle and the parking spot in real time) directly in the user's field of view. Compared to static identifiers, this directly supports efficient boarding and prevents misidentification. This trait of AR-based shuttle identification can also increase operational efficiency from a service-provider perspective by reducing boarding errors and delays, thereby improving shuttle-passenger matching. This potential reinforces the role of AR not only as a usability feature but also as an enabler of smoother and more efficient shared mobility services. Hence, this work directly refers to this research gap:

RQ2: Do users rate the vStop HMI AR prototype positively for UX, acceptance, and cognitive workload during shuttle identification?

Besides the evaluation regarding these formulated research questions, the current study also tries to gain insights about how participants perceive the overall usefulness of the vStop HMI and the AR technology in each scenario. Eventually, this research tries to give a comprehensive proof-of-concept of the vStop HMI in the context of a SAMOD user journey.

It is important to note that mobile AR technology still bears limitations for the scenarios of interest because of its vulnerability to the visual conditions and spatial constraints (especially outdoors). Furthermore, object detection of, and real-time interaction with moving physical objects (like a shuttle) are technical challenges of mobile AR, too (Ghasemi et al., 2022; Lee et al., 2022). To ensure a high level of standardization, feasibility, and immersion, this experimental user study was conducted in a virtual reality (VR) setting. Accordingly, the AR technology and the mobile device were simulated with the use of VR equipment throughout this explorative investigation, similar to Lanzer et al. (2023).

2. Materials and methods

2.1. Sample

The participants for this user study were recruited via personal contacts and social media postings. Additionally, mailing lists and subject databases of Technical University of Berlin, Germany, and of the Institute of Transportation Systems of the German Aerospace Center (DLR) were used to attract study participants. Furthermore, calls for participants were circulated at restaurants, cafeterias, and libraries located in vicinity to the research institute.

Participants had to be between the ages of 18 and 40 years to create a homogeneous sample. Normal or corrected-to-normal vision and the absence of mobility impairments were required to ensure care-free interaction with the VR equipment. Since the study was conducted in German, only participants with very good knowledge of German were allowed to take part. In addition, individuals with known pregnancies or those at risk of provoked epileptic seizures due to VR exposure were excluded.

In total, $N = 44$ ($f = 34$ %, $m = 61$ %, $d = 5$ %) participated in the user study. Average age was 27.77 (SD = 5.29; from the age of 18 to 40). Overall, the sample can be described as a cohort of young German adults from urban areas with a comparatively high level of formal education, as 86 % held a high school diploma (Abitur) and 57 % were currently enrolled as university students. The sample showed a notable level of familiarity with the research context: 64 % of participants had previously used on-demand mobility services, and 30 % had experience with ride pooling services, each at least once in private settings.

The sample's technology affinity was above average, with a mean ATI score of 4.22 (SD = 0.81; using 6-point Likert Scale from 1 = "completely agree" to 6 = "completely disagree") (Franke et al., 2019). This corresponds with the sample's experience with mixed reality technology. 84 % reported prior use of VR at least once, 60 % had used handheld AR applications, and 12 participants reported prior experience with AR glasses. During the VR study, participants reported a fairly high level of immersion ($M = 4.89$, SD = 1.32; using a 7-point Likert scale, 1 = "strongly disagree", 7 = "strongly agree"), measured with the immersion subscale of the standardized TUI questionnaire (Kothgassner et al., 2025). On average, the participants were quite comfortable to maneuver with the provided equipment in the VR environment ($M = 3.18$, SD = 1.61; "I found it difficult to handle the VR shoes" using a 7-point Likert scale from 1 = "strongly disagree", 7 = "strongly agree"). Simulator sickness was no issue for the participants ($M = 2.84$, SD = 1.96; "I experienced sickness or vertigo in the VR environment" using a 7-point Likert scale from 1 = "strongly disagree" to 7 = "strongly agree"). One participant had to terminate the study due to simulator sickness, and their data was excluded.

All participants reported prior use of smartphone pedestrian navigation apps (e.g., Google Maps). Of these, 45 % used such apps weekly and 25 % reported daily use. Only 2 participants had used mobile maps navigation just once prior to the user study (on a 5-point Likert scale, 1 = "Once", 2 = "several times per year", 3 = "several times per month", 4 = "several times per week", 5 = "daily"). In the user study, participants recorded that the handling of the simulated smartphone in the VR environment (via controller) felt somewhat natural ($M = 5.11$, SD = 1.21; "Handling of the VR smartphone felt natural" using a 7-point Likert Scale from 1 = "strongly disagree", 7 = "strongly agree")

About 80 % of participants recorded a relatively strong interest in automated vehicles (above 4 on a 7-point Likert scale; 1 = "no interest at all", 7 = "very strong interest"). Although 98 % of the participants had already heard about automated vehicles, only 7 % had ever ridden in one.

The study was designed and conducted in accordance with the Declaration of Helsinki. Informed consent was obtained from participants before the experiment. All participants volunteered and were financially compensated with 15€.

2.2. Dependent variables

The following dependent variables were used in the explorative user study to investigate the effects of the vStop HMI on the participants.

2.2.1. Cognitive workload

In general, (mental) workload can be defined as the degree of cognitive activation while processing a task over time (Longo et al., 2022). Hence, this dependent variable assessed the mental activation level during prototype use in the different scenarios. Therefore, the standardized NASA-TLX questionnaire was used (Hart and Staveland, 1988). This variable indicated whether the HMI is subjectively rather complicated or simple to interact with. It was modified to a 10-point Likert scale (6 items, 1 = "very low demand"; 10 = "very high demand") to make it easier for the participants to answer. Weighting of each item as suggested by the questionnaire authors was not performed to enable quick filling of all questionnaires and reduce complexity. Hence, in this work the cognitive workload is presented as a total score of the NASA-TLX raw version.

2.2.2. Acceptance

The term acceptance is used to describe a prediction whether customers would potentially use a product or technology in the future (Venkatesh et al., 2003). Hence, to assess potential user adoption of the vStop HMI, participants' acceptance was captured using the German version of the standardized UTAUT2 questionnaire (Harborth and Pape, 2018). However, to account for the prototypical character and the context of HMI use, only 2 subscales (*usability* and *intention to use*) were used (3 items each, 7-point Likert scale; 1 = "don't agree at all"; 7 = "totally agree"). Overall acceptance of the prototype is presented in a joint UTAUT2 score and could potentially indicate positive impact of the HMI prototype in the future.

2.2.3. User experience

To capture the UX during HMI use, the standardized UEQ-S was used (8 items, 7-point Likert scale; −3 = negative; 3 = positive evaluation) (Schrepp et al., 2017). UX plays an important role to evaluate the participants' perception of the prototype in terms of *pragmatic quality* (ease of use, 4 items) and *hedonic quality* (joy of use, 4 items).

2.2.4. Qualitative user feedback

In order to understand user behavior and attitudes towards the vStop HMI prototype, a qualitative interview was conducted after each scenario to gather subjective feedback. Participants were asked about positive aspects ("What did you like about the AR-HMI concept?"), negative aspects ("What did you dislike about the AR-HMI concept?"), and potential improvements ("How would you improve it, and why?").

2.3. Study procedure

To start this investigation, the participants received general instructions and filled out necessary documentation. Then, the participants got to know the VR setup and had time to practice in an extra VR training environment, which resembled the one used later in the studies. Participants were asked to empathize with the traffic situation and act accordingly, so that they did not perceive the task merely as a video game. After the training, participants received further instructions about the actual investigation which was divided into two parts of the SAMOD user journey. First, a navigation scenario was presented in two trials. Participants were split into two groups and had to find a virtual stop by following the instructions given by the respective vStop HMI variant (between-subject design). In the second scenario, the groups were merged again. Participants had to identify the correct shuttle at the pick-up location in two trials with the help of the same vStop HMI. During the study, the investigator followed a worksheet to ensure a standardized procedure. Each part of the user study was accompanied by a corresponding set of questionnaires. The final part of this investigation was the debriefing and participants answered another set of sociodemographic and control questions (e.g., immersion and handling of VR equipment). Eventually, they received a detailed explanation of the research objective, and completed a form to receive compensation. For an overview of the study procedure, see Fig. 1.

2.4. VR setup of the user study

The stimulus material was developed and presented using the Unreal game engine (Version 4.27). Ensuring a high level of standardization and presentation quality, a highly capable VR PC with a state-of-the-art graphic processor unit (model: NVIDIA GeForce RTX 3080) was used in all study conditions. For the visualization of the VR environment a Head-mounted-display (HMD) from HTC (Vive Pro) with two AMOLED-Displays (each 3.5", 1440×1600 pixels; 110° field of view in total) and the HTC controller as an input device was used.

2.4.1. VR environment

The VR environment presented a 3D model representation of Tostmannplatz, a suburban area in Braunschweig, Germany, created with high level of detail (Fischer et al., 2022; Rehm et al., 2023). Buildings and vegetation were added to give the environment a more realistic appearance (although an exact replication of the real-world area was not the goal). Lighting was set to represent midday conditions. The space was also populated with moving, standing, and sitting pedestrians, either alone or in small groups of up to four. Moving and parked vehicles of various kinds (passenger cars, AVs, minivans, buses) and colors were included to convey the impression of a near-future mixed traffic scenario. The behavior of the population was scripted and thus identical across all conditions. However, collisions or critical encounters between participants and the placed actors were systematically prevented. The standard soundscapes (e.g., from vehicles, birds, dogs) were also

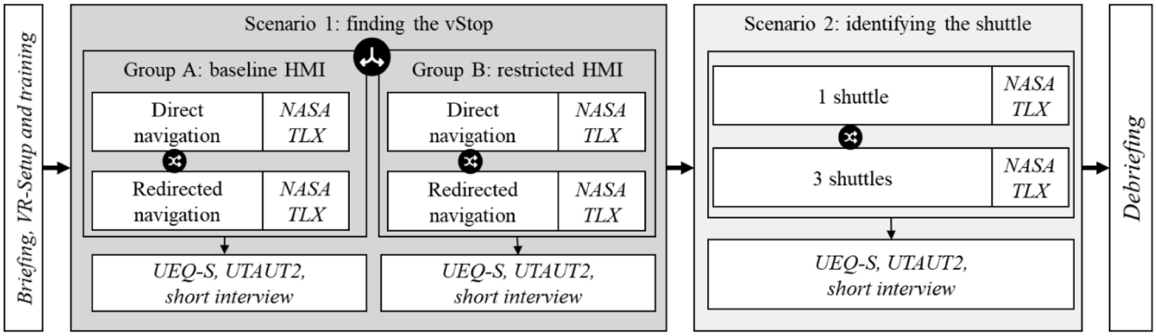


Fig. 1. Procedure of the experimental user study, addressing two SAMOD user journey scenarios.

implemented. Fig. 2 shows the VR environment and illustrates its similarities to the real location.

2.4.2. VR interaction

In the first scenario, participants had no spatial restriction and could maneuver freely in the VR environment. This was possible due to the use of the Cybershoes equipment (Fig. 3, b). They enable longitudinal character movement so that even larger distances can be covered. A 360° rotatable chair allowed for change of directions. Walking speed was set to moderate. To experience the study conditions with an appropriate level of immersion, participants wore an HMD (Figs. 3, a; 4). An HTC Vive Pro controller simulated smartphone use throughout the study. To access the simulated AR device in VR, participants had to use the index finger and press the trigger button on controller (Fig. 5). As long as they pressed the trigger, the smartphone appeared in front of the field of view and the vStop HMI was visible. Additionally, a press with the thumb on the trackpad allowed an "Okay" input to launch into the AR information element view and start the navigation task.

3. First part of the user study: the scenario of finding the vStop

The next section elaborates on the user journey scenario of reaching to the vStop location efficiently. Here, the challenge arises that the AR HMI should be useful for finding the vStop and prevent negligent behavior.

Hence, the first part of the explorative user study answers RQ1*: Compared to a baseline variant, how does restricting the AR information during walking affect UX, acceptance, and cognitive workload ratings of the vStop HMI?*

3.1. Stimulus material

The general concept of the mobile AR HMI is based on the principles of user-centered design and was presented in Hub et al. (2023) and Hub and Oehl (2022). For this investigation, the concept was iterated and transferred to the AR-within-VR approach. The screen of the simulated mobile device was divided into two sections. The lower part at the bottom displayed the service information of a fictitious mobility service provider (Fig. 6). This part, inspired by conventional on-demand mobility service provider apps, showed a picture of the shuttle, including a shuttle number for identification ("#11″), the fictitious pick-up time ("boarding in 3 min"), and a dummy travel progress bar at the bottom.

The upper part of the screen presented the actual HMI with AR navigation information elements in device perspective rendering (Čopič Pucihar et al., 2014). The Start Element gave the user a clear hint that the navigation is about to begin (Fig. 6, b). Since the user is standing upright, the mobile device is very likely to be tilted downwards slightly.

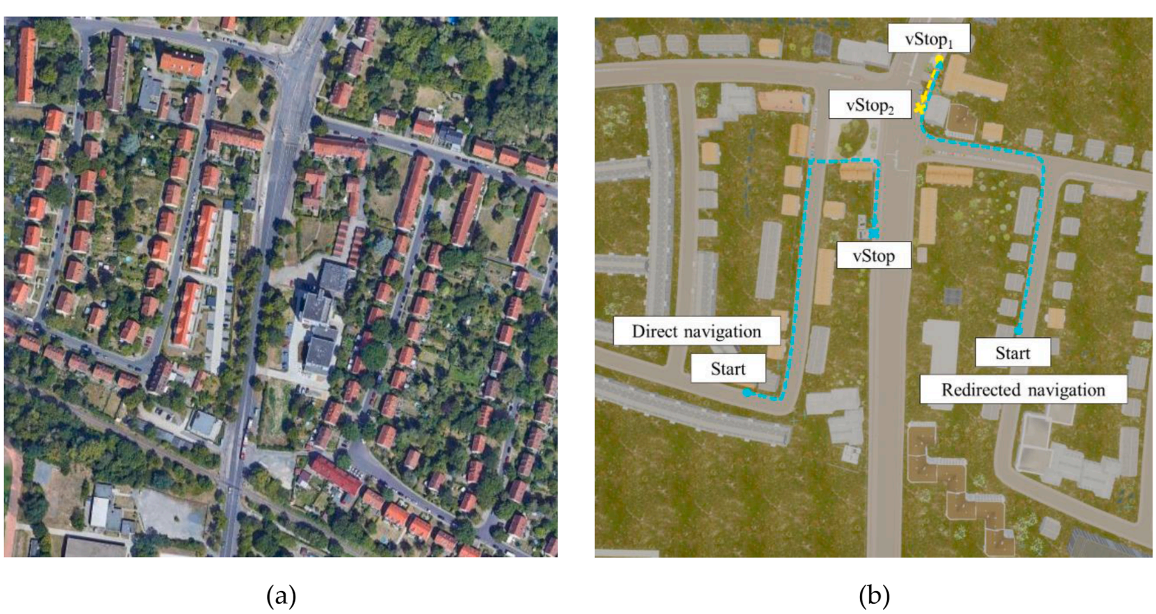


Fig. 2. Overview of the user study environment. (a) satellite image of the real Tostmannplatz Square in Braunschweig (source: Google Maps), (b) 3D Model of the very same area used in the VR user study (source: DLR), navigation trials (scenario 1) were conducted with the marked routes, identification trials (scenario 2) were conducted at $vStop_2$ position.

(a) (b)

Fig. 3. Wearable VR equipment used in the user study. (a) Vive Pro HMD with controller, (b) strapped Cybershoes.

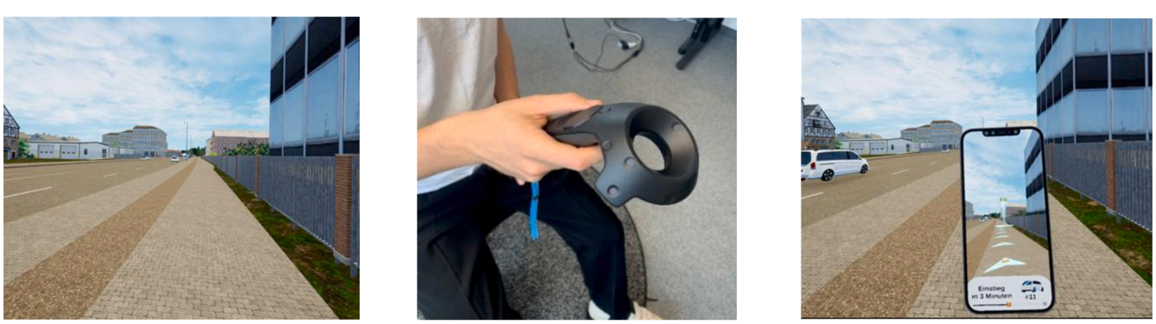
Fig. 4. Study participant wearing the VR headset to see, and sitting on the 360° rotatable chair and wearing the Cybershoes to move in the VR environment.

Hence, the circular shaped object is lying on the ground right in front of him/her. The object is relatively large to draw attention. The elements also show the emoji and an arrow to give identification and guidance (inspired by sign EN ISO 7010).

To show the pathway, chevron-shaped elements were used (Fig. 6, c, d). The elements were placed on the ground and formed a line along the route. The elements adapted the position dynamically to the movements of the user, so the nearest element was always directly in front, which made finding the pathway elements very simple. To highlight sharp turns, the vStop HMI showed a floating triangular-shaped object (see Fig. 6, c). It was floating approximately 2 m above the ground. It was positioned in slight periphery of the pathway, so users would notice it from a few meters distance but the view was not blocked. This element also shows the emoji and an arrow to give guidance and identification. The pick-up location and the waiting area elements marked the end of the navigation and were highlighted by a standing object and the end of the route (Fig. 6, d, e). The German bus stop sign (VZ 224 StVO), a learned symbol, was used to indicate the pick-up position. The waiting area was a round-shaped object, similar to the start object. The form of the standing 3D information element (inverted pyramid shape) was designed to guide user's attention from top (bus stop sign) to bottom (waiting area). Emoji and arrows indicated that the user could wait here safely (inspired by sign ISO 7010 E 007). To indicate the wrong way or wrong orientation of the user, a circular-shaped floating information element was used (Fig. 6, a). Here, the symbol of modern prohibitory traffic signs (Vienna Convention, C, 1[a], (UNECE, 2006)) ensured familiarity. The sign was adapted to the cyan color scheme with a glowing crossbar.

3.2. Experimental conditions

This scenario consisted of two navigation trials, using a 2 × 2 mixed design, with the two factors *navigation task* and *restriction of AR information*. The within-subjects factor *navigation task* included the levels "direct navigation" and "redirected navigation". These factor levels represent two similar but distinct use cases of reaching a virtual stop. Although both trials had approximately the same walking distance of 300 m through a suburban VR environment, sharp right and left turns and one street crossing, they were not directly comparable. Instead, the trials represent two realistic variations of the same task. The direct navigation trial ended when the participants reached the vStop destination presented on the HMI (see Fig. 7, a). The redirected navigation trial included a vStop relocation, meaning that once participants arrived at the initially communicated vStop_1 position, the pick-up location changed to vStop_2. For example, in a future connected mobility system the traffic management system could recognize a blocked stopping



(a) (b) (c)

Fig. 5. By pressing the trigger on the VR controller with the index finger, participants called up the simulated AR device to see the vStop HMI and receive information. (a) participants field of view when trigger is not pressed, (b) index finger placed on the trigger of the VR controller, (c) participants field of view as long as the trigger is pressed.

Fig. 6. AR information elements of the vStop HMI for the navigation task. (a) wrong direction symbol, (b) start position and pathway, (c) pathway and turning symbol, (d) pathway and vStop, (e) vStop element with stop sign and waiting area. All: fictitious service information on bottom of the screen.

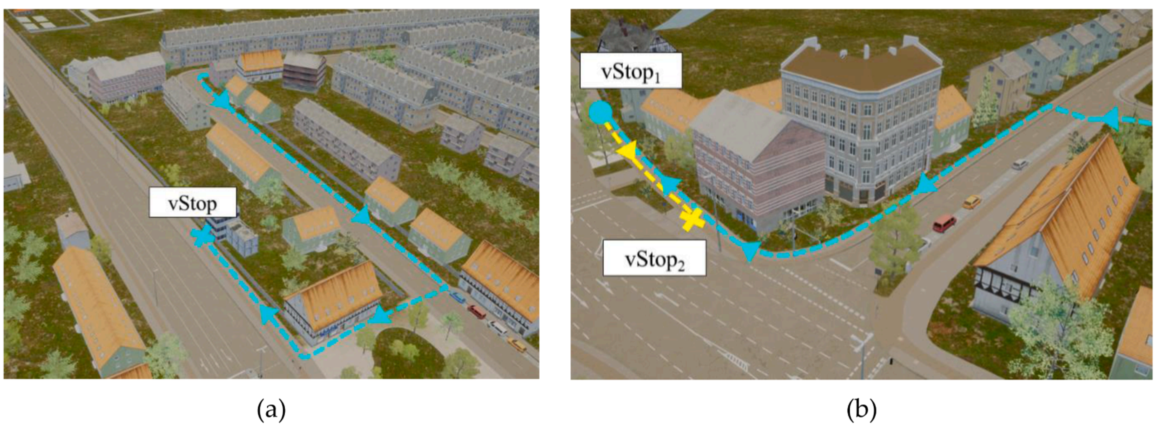


Fig. 7. Routes for the navigation tasks. (a) direct navigation to vStop location (pathway in blue), (b) redirected navigation with the first route to vStop$_1$ (in blue) and rerouting to vStop$_2$ (in yellow).

position and relay this information to the routing service. Accordingly, the vStop HMI informed users about the updated pick-up location through a set of pop-up screens stating "Your pick-up location has been moved" and "The route to your pick-up location is being recalculated". Afterwards, participants had to perform a 180° turn to navigate to the new location (approx. 40m away). Hence, the redirected navigation use case consisted of two consecutive navigation tasks (see Fig. 7, b). Participants experienced the navigation use cases balanced order.

During both trials, participants started facing the wrong direction and had to find the way to the vStop solely by following the instructions on the mobile HMI in unfamiliar territory. They could move freely within the VR environment. Apart from HMI guidance, no additional cues were provided regarding where to go and how to reach the pick-up location.

The second factor concerned the *restriction of AR information* on the vStop HMI prototype. This restriction was applied as between-subject factor (A/B test) with the conditions "no restriction to the AR information" (group A) and "restriction of AR information while walking" (group B). Factor exposure to the participants, and thus group assignment, followed a balanced order.

Participants of group A (baseline) were able to access the navigation information presented on the simulated smartphone at all times and as frequently as they wished. Group B (treatment), by contrast, had restricted information access on the mobile AR vStop HMI to prevent users from consuming the information while walking. A simple pop-up screen covered the entire display of the simulated device (see Fig. 8, b). It was triggered by any longitudinal movement of the participants. As soon as they came to a standstill, the pop-up disappeared and the AR information elements reappeared (with a minimum pop-up appearance time of 1s).

However, participants in both groups were still able to request to view the device itself, only the presentation of information on the smartphone differed.

3.3. Procedure to investigate the use of the vStop HMI variants in the first user journey scenario

In this first part of the user study, the participants were assigned to group A or B in balanced order and received instructions regarding the general functionality of the vStop HMI. Afterwards, the vStop HMI and all associated information elements were explained in detail, questions regarding the interface were answered, and the purpose of each feature was clarified. For group B, the limited AR information access was presented as a "safety feature". It was ensured that all participants fully understood the vStop HMI.

Thereafter, the investigator instructed participants to mentally place themselves in the situation of the SAMOD scenario (taking a shuttle to the airport). Their task was to reach to the vStop location within 3 min to catch the automated shuttle. Following this instruction, participants began their first trial. After successfully completing a trial, they responded to a set of questions on a tablet computer. The next trial was then conducted, again followed by questionnaire-based responses. The

(a) (b)

Fig. 8. Overview of the HMI variants during the navigation task. (a) View of group A that used the HMI without information restriction. (b) View of group B that used the HMI with the treatment of information restriction when walking.

first part of the user study concluded with a brief qualitative interview about likes, dislikes and potential improvements of the vStop HMI prototype.

3.4. Results

This section focuses on the data analysis and presents the results of the questionnaires and qualitative user feedback of the VR user study.

3.4.1. Data analysis

In order to apply statistical tests to the questionnaire data, participants answers were analyzed. The Shapiro-Wilk test showed nonparametric distribution across all variables. Therefore, the Wilcoxon Rank Sum test was applied to conduct inferential statistics analysis. The official UEQ-S data analysis guidelines for outlier detection was applied for each group (Laugwitz et al., 2008). Consequently, data of 1 participant was excluded for group B. For NASA-TLX and UTAUT2 variables analysis for outliers followed the 1.5 interquartile range method. Initially, the analysis showed 3 outliers in the redirected navigation trial for each group's NASA-TLX questionnaires. However, after manual examination of individual data and impact on internal consistencies, outliers were not removed.

In the following, internal consistency of the participants' answers was analyzed using Cronbach's alpha method. The short version of the UEQ covers two dimensions of user experience. The *pragmatic quality* (4 items) describes whether the HMI prototype is effective to solve a certain task. *Hedonic quality* (4 items) covers the aspect whether the HMI prototype provides joy to the users.

As for the NASA-TLX raw, 6 items represent the subjective workload and sum up to a total score (Hart and Staveland, 1988).

The UTAUT2 questionnaire was used to measure overall acceptance of the HMI prototype. Originally, 8 subscales apply for the UTAUT2 questionnaire (Harborth and Pape, 2018). This study used a modified version, only using the *usability* and *behavioral intention* subscales with 3 items each. Mostly, the results were very reliable and suitable for interpretation as alpha values were high to very high ($\alpha > 0.80$). Values for the UEQ-S subscales *hedonic quality* for groups A and B were at acceptable level and interpretable, too ($0.60 < \alpha < 0.80$). However, data for *pragmatic quality* of the UEQ-S in group B showed a very low alpha value ($\alpha < 0.60$) and should therefore be interpreted with caution (Streiner, 2003).

3.4.2. Cognitive workload

The cognitive workload during HMI use (for both variants) was evaluated with the NASA-TLX. In the direct routing trial, the workload during use was rated very low for of both HMI variants (see Table 1), as all confidence intervals are below the scale average (10-point Likert scale). Only for item *frustration* a significant difference was found. Overall, the *TLX total* score of HMI B shows a significantly higher evaluation compared to HMI A.

In the redirected routing trial, no significant differences between the evaluation of HMI variants A and B were found (see Table 2). Descriptively however, HMI A received lower and less divergent ratings by the participants across all items than HMI B. Still, overall TLX values are low for both HMI variants in this trial, too.

3.4.3. Acceptance

The acceptance of the vStop HMI variants was evaluated using a modified version of the UTAUT2 questionnaire (7-point Likert scale). Results show the comparison of both HMI variants after completion of both navigation trials (see Table 3). Although, no statistically significant differences appeared, HMI B received slightly higher ratings. In total, both prototype variants received similarly high scores for acceptance and potential future adoption.

Table 1
Cognitive workload ratings of the vStop HMI in the direct navigation trial (n_A = 22, nB = 22, between subject, Wilcoxon Rank Sum test).

Direct navigation NASA-TLX	Group A		Group B			
	M_{emp} (SD_{emp})	95 % CI [LL, UL][1]	M_{emp} (SD_{emp})	95 % CI [LL; UL][1]	W[2]	p[3]
Mental demand	2.50 (1.41)	1.87; 3.12	3.45 (1.71)	2.70; 4.21	161.5	.056
Physical demand	3.36 (2.30)	2.34; 4.38	3.68 (2.10)	2.75; 4.61	214	.511
Temporal demand	3.09 (1.60)	2.38; 3.80	3.55 (2.48)	2.44; 4.65	233.5	.846
Performance	2.14 (1.81)	1.34; 2.94	3.27 (2.90)	1.99; 4.56	174	.098
Effort	2.68 (1.62)	1.97; 3.40	3.77 (2.20)	2.80; 4.75	169.5	.080
Frustration	2.14 (1.13)	1.64; 2.64	3.77 (2.02)	2.88; 4.67	114.5	< .01
Total score	2.65 (1.27)	2.09; 3.22	3.58 (1.38)	2.97; 4.20	147	< .05

[1] Confidence interval with lower (LL) and upper limits (UL)
[2] test statistic that indicates the sum of positive rank numbers
[3] parameter p can only be estimated since ties exist in the data.

Table 2
Cognitive workload ratings of the vStop HMI in the redirected navigation trial ($n_A = 22$, $n_B = 22$, between subject, Wilcoxon Rank Sum test).

Redirected navigation NASA-TLX	Group A		Group B		W[2]	p[3]
	M_{emp} (SD_{emp})	95 % CI [LL, UL][1]	M_{emp} (SD_{emp})	95 % CI [LL; UL][1]		
Mental demand	2.82 (1.87)	1.99; 3.65	3.86 (2.51)	2.75; 4.98	184	.168
Physical demand	2.95 (1.96)	2.08; 3.83	4.05 (2.55)	2.91; 5.18	180	.141
Temporal demand	2.95 (1.99)	2.07; 3.84	3.23 (2.37)	2.18; 4.28	235.5	.886
Performance	2.41 (2.32)	1.38; 3.44	2.73 (2.51)	1.61; 3.84	214	.499
Effort	2.50 (1.44)	1.86; 3.14	3.55 (2.50)	2.44; 4.65	194	.245
Frustration	2.41 (1.56)	1.72; 3.10	3.14 (2.29)	2.12; 4.15	208	.417
Total score	2.67 (1.46)	2.03; 3.32	3.42 (1.91)	2.58; 4.27	173	.107

[1] Confidence interval with lower (LL) and upper limits (UL).
[2] test statistic that indicates the sum of positive rank numbers.
[3] parameter p can only be estimated since ties exist in the data.

Table 3
Acceptance ratings of the vStop HMI after both navigation trial ($n_A = 22$, $nB = 22$, between subject, Wilcoxon Rank Sum test).

Navigation scenario UTAUT2 mod.	Group A		Group B		W[2]	p[3]
	M_{emp} (SD_{emp})	95 % CI [LL, UL][1]	M_{emp} (SD_{emp})	95 % CI [LL; UL][1]		
Usability	5.09 (1.31)	4.51; 5.67	5.42 (1.10)	4.93; 5.91	209.5	.451
Intention to use	4.03 (1.45)	3.39; 4.67	4.77 (1.48)	4.11; 5.43	165.5	.073
Total score	4.56 (1.13)	4.06; 5.06	5.10 (1.16)	4.58; 5.61	181	.155

[1] Confidence interval with lower (LL) and upper limits (UL).
[2] test statistic that indicates the sum of positive rank numbers.
[3] parameter p can only be estimated since ties exist in the data.

3.4.4. User experience

In this user study, the user experience was measured with the short version of the User Experience Questionnaire (UEQ-S, 7-point Likert scale; −3, 3). Again, results show the comparison of both HMI variants after completion of both navigation trials. (see Table 4). Both HMI variants show high *pragmatic quality* ratings without significant differences. The *hedonic quality* subscale shows no significant differences between HMI A and B. Although HMI B received higher ratings descriptively, both can be described as rather neutral. The 95 % confidence intervals for both HMI variants are above the 0.80 threshold to indicate positive evaluation in terms of *pragmatic quality*.

Table 4
User experience ratings of the vStop HMI after both navigation trials ($n_A = 22$, $n_B = 21$, between subject, Wilcoxon Rank Sum test).

Navigation scenario UEQ-S	Group A		Group B		W[2]	p[3]
	M_{emp} (SD_{emp})	95 % CI [LL, UL][1]	M_{emp} (SD_{emp})	95 % CI [LL; UL][1]		
Pragmatic quality	1.84 (0.94)	1.45; 2.24	1.92 (0.72)	1.61; 2.22	232	.990
Hedonic quality	0.59 (1.00)	0.17; 1.01	1.06 (0.98)	0.64; 1.48	174	.168

[1] Confidence interval with lower (LL) and upper limits (UL).
[2] test statistic that indicates the sum of positive rank numbers.
[3] parameter p can only be estimated since ties exist in the data.

3.4.5. Qualitative user feedback

The following subsection presents the qualitative user feedback regarding the vStop HMI prototype (both variants) in the navigation scenario. In general, the information elements were very easy to understand and the overall assistive character of HMI prototype for the navigation task stood out to the participants. Some participants criticized that the AR HMI could only project information elements in a certain distance and that it would also lead to cluttering. The lack of an overview of the route was criticized and the addition of some sort of a 2D mini-map to get an overview was desired ($n = 13$). The aspect that received most negative feedback was the information restriction treatment, as 32 % of the participants of group B felt patronized by it and led to frustration since it would cost time to stop ($n = 4$). When asked about it, 63 % of the participants articulated their disliking of the information restriction treatment as they had to constantly memorize where to go and turn. 6 participants acknowledged the safety feature. The qualitative user feedback revealed that participants of group B mostly used on the turning arrow elements for guidance, while participants of group A mainly focused the pathway elements on the ground.

3.5. Discussion of the results of the first part of the user study

The results of scenario 1 showed that the vStop HMI prototype was very helpful for solving the given task. In both navigation trials, all participants managed to solve the task successfully without problems. In general, it is important to mention that in this part of the user study, the *physical demand* ratings were mostly influenced by the VR equipment and are identical for both groups. In the direct navigation trial, HMI B received a significantly higher NASA-TLX score than HMI A. Accordingly, restricting the access of AR navigation information during use increased the overall subjective workload, with *frustration* levels in particular rising significantly for group B during HMI use. Participants were annoyed by the stop-and-go behavior, as many reflected in the interviews. Yet, both groups reported quite low total workload ratings as both 95 % CI scores were below the scale average of 5 in both navigation trials. Although the differences were statistically not significant, the *mental demand* and *effort* ratings underline the generally simpler handling of HMI A. For the trial of redirected navigation, no significant differences in workload were found, and evaluation of subjective workload was almost identical across trials for group A. Hence, the use case of vStop relocation ($vStop_1$ to $vStop_2$) did not greatly irritate group A participants. In contrast, workload evaluation of group B decreased in the redirected navigation trial. Especially, *temporal demand, performance* and *frustration* decreased descriptively, which could have implications for the future design of vStop grids and shuttle-passenger matching algorithms. It seems that customers would not experience excessive stress or irritation when confronted with flexible pick-up relocations by a mobility service provider.

The general assistive character of vStop HMI prototype in this scenario was highlighted by the UEQ-S results. No statistical differences between the groups were found. Since the *pragmatic quality* subscale showed low internal consistency for group B, the reliability of inferential statistics could be somewhat limited. Nevertheless, the results indicate that both prototype variants were very helpful for the participants in the navigation task. Both HMIs showed almost identically positive ratings for *pragmatic quality*, that yielded results significantly above the questionnaire's threshold (> 0.80). Hence, the vStop HMI prototype was very supportive in the investigated scenario and builds on latest findings (Hub and Oehl, 2022). As for *hedonic quality*, which yielded rather neutral ratings of the vStop HMI prototype across both groups, results align with previous research (Hub and Oehl, 2022). This outcome is acceptable at this stage of the user-centered design process.

The results for acceptance show no significant differences between both HMI variants either. Compared to the UX evaluation, a similar trend was visible, as group B recorded descriptively higher ratings across all items. Again, this indicates participant's acknowledgement for the "safety feature" approach, although both groups recorded only medium overall ratings.

Complementing the quantitative results, the post-trial interviews revealed that the HMI prototype was generally very well received by the participants. All AR information elements were considered easy to understand and helpful. However, many participants mentioned the absence of a map overview as a desired feature. Providing such an overview to the route to allow for self-paced navigation could further strengthen the assistive character of the vStop HMI. At the same time, the majority of group B expressed strong disliking toward the information restriction treatment of the vStop HMI. However, this aversion was not reflected in the questionnaire ratings. In summary, this first part of the user study showed that the AR information restriction treatment for the vStop HMI did not negatively affect UX or acceptance. Applying such a restriction to the AR interface to prevent users from stepping into potentially dangerous situations appears reasonable. However, information restriction mechanisms should be carefully designed, taking into account specific user needs and concerns. Future design iterations could emphasize on a more adaptive and less radical approach, for example, targeting specific circumstances and areas of potential harm, such as street crossings (Frej et al., 2022).

4. Second part of the user study: the scenario of identifying the shuttle

The next section elaborates on the user journey scenario of identifying the shuttle. Here, the challenge of easy and effective SAV identification, even in more complex situations, arises.

Consequently, the second part of the explorative user study answers RQ2: *Do users rate the vStop HMI AR prototype positively for UX, acceptance, and cognitive workload for shuttle identification?*

4.1. Stimulus material

In the following, the HMI elements for the shuttle identification scenario are presented. Again, the general concept of the mobile AR HMI is based on the principles of user-centered design (Hub and Oehl, 2022; Hub et al., 2023). Just like in the previous part of the user study, the concept was iterated and adapted for the VR setup. The screen of the simulated mobile device was divided into two sections. The lower section displayed the service information of a fictitious mobility service provider and included a picture of the shuttle, its number for identification ("#11″), the fictitious pick-up time ("Boarding now!"), and a dummy travel progress bar at the bottom. The upper section of the screen presented the actual HMI with device perspective AR rendering (see Fig. 10, b) (Čopič Pucihar et al., 2014). To identify the correct shuttle for boarding, a diamond-shaped AR information element was used. This highlighter was floating above the shuttle and constantly stayed with the vehicle (Fig. 9, a). This information element also displayed an emoji to facilitate identification. Additionally, the exact stopping position was shown using a cyan-colored AR carpet with glowing corners (Fig. 9, b). This element was visible to the users even before the shuttle had arrived. Other vehicles were allowed to drive over the stopping position element.

4.2. Experimental conditions

The second scenario of the user study focused on identifying the approaching shuttle while waiting curbside. In this scenario, participants were not able to walk in VR. Standing on a sidewalk near a stop bay where the shuttle would arrive to pick them up, the task was primarily observational. The VR environment depicted the pick-up location from the redirected navigation trial. The vStop HMI provided AR-based information to help participants identify the correct shuttle. As in the first scenario, the device could be accessed by pressing and holding the trigger on the HTC Vive controller (Fig. 10).

A within-subject design with the single factor *number of approaching shuttles* was used. All participants experienced both factor levels "1 shuttle" and "3 shuttles" in balanced order. These factor levels represent two realistic use cases of shuttle identification. To differentiate the number of identically looking shuttles arriving at the pick-up position, two traffic conditions were simulated: a low-traffic condition (e.g., single shuttle at noon) and high-traffic condition (e.g., three shuttles during rush hour). In both cases, the overall surrounding traffic density adjusted accordingly. The correct shuttle (automated shuttle, DLR UMV People Mover (DLR, 2020)) to be identified displayed the number 11 on its body. In the three-shuttle condition, two additional shuttles, identical in type and color (as all belonged to the same mobility service provider), also stopped at the same pick-up location (e.g., to pick-up other customers). These shuttles displayed different vehicle numbers and arrived prior to shuttle labeled 11. All shuttles approached the stopping position from the left side of the participant's field of view (reflecting traffic in Germany) and executed appropriate stopping maneuvers (Hub et al., 2022). In both conditions, the shuttles stopped in the designated stop bay. However, in the "3 shuttles" condition, they lined up in sequence. For each use case, the duration from the beginning of the scenario until the arrival of the first shuttle was fixed at 30 s.

4.3. Procedure to investigate the use of the vStop HMI in the second user journey scenario

In the second part of the user study, all participants used the same vStop HMI, once groups A and B were dissolved. After the investigator explained the relevant vStop HMI information elements for this user

(a) (b)

Fig. 9. vStop HMI information elements to identify the shuttle. (a) diamond shaped shuttle highlighter, (b) stopping position highlighter.

(a) (b)

Fig. 10. Overview of the scenario to identify the shuttle. The more complex use case with three shuttles at the pick-up location is shown. (a) view of the shuttles stopped at vStop location, (b) view of the stopped shuttles with using the vStop HMI to identify the correct shuttle.

journey scenario, participants received their instructions. As before, they were asked to mentally adopt the role of a passenger taking a shuttle to the airport. However, since they had already navigated to the vStop location in the previous scenario, they now waited curbside to be picked-up by their shuttle. After completion of each shuttle identification trial, the participants completed a set of questionnaires. Again, this part of the user study concluded with a brief qualitative interview about likes, dislikes and potential improvements of the vStop HMI prototype.

4.4. Results

This section focuses on the data analysis and presents the results of the questionnaires and qualitative user feedback of the VR user study.

4.4.1. Data analysis

Again, participants answers were analyzed and showed nonparametric distribution across all variables. Consequently, the Wilcoxon Rank Sum Test for inferential statistics analysis was applied.

Outlier analysis followed the same procedure as in the first user study. In total, this led to the removal of participant data in 4 cases. Cronbach's alpha method for analysis of the internal consistency of the participants' answers in the used questionnaires followed. Again, the results were very reliable and suitable for interpretation as alpha values were high to very high ($\alpha > 0.80$). Only the NASA-TLX results showed very low alpha values ($\alpha < 0.60$) in both conditions and should therefore be interpreted with caution (Streiner, 2003).

4.4.2. Cognitive workload

In both trials of the shuttle identification scenario, the participants rated the overall workload of using the HMI during the identification task very low (see Tables 5 and 6). In fact, all items across both trials showed significantly lower workload than the self-established threshold for positive evaluation (below scale average, 10-point Likert scale).

4.4.3. Acceptance

The acceptance of the vStop HMI to assist users in the scenario of shuttle identification was recorded with a modified version of the standardized UTAUT2 questionnaire after completion of both trials (see Table 7). All results, total score and subscales, showed an overall acceptance rating significantly above the self-established threshold (above scale average, 7-point Likert scale).

4.4.4. User experience

Results of the UEQ-S (7-point Likert scale; −3 = negative; 3 = positive) for the shuttle identification scenario were recorded after both trials and are presented in Table 8. The HMI's *pragmatic quality* exceeded

Table 5
Cognitive workload ratings of the vStop HMI in the identification trial of one shuttle ($N = 44$, Wilcoxon Rank Sum test).

Identification scenario	1 Shuttle				
NASA-TLX	M_{emp} (SD_{emp})	95 % CI [LL; UL][1]	M_{crit}	V^2	p^3
Mental demand	2.07 (1.37)	1.65, 2.48	< 5.00	8.5	< .001
Physical demand	1.34 (0.83)	1.09, 1.59	< 5.00	1	< .001
Temporal demand	1.70 (1.32)	1.30, 2.11	< 5.00	10.5	< .001
Performance	2.45 (2.61)	1.66, 3.25	< 5.00	155.5	< .001
Effort	1.41 (0.69)	1.20, 1.62	< 5.00	0	< .001
Frustration	1.50 (1.07)	1.18, 1.82	< 5.00	3	< .001
Total score	1.75 (0.80)	1.50, 1.99	< 5.00	0	< .001

[1] Confidence interval with lower (LL) and upper limits (UL).
[2] test statistic that indicates the sum of positive rank numbers.
[3] parameter p can only be estimated since ties exist in the data.

Table 6
Cognitive workload ratings of the vStop HMI in the identification trial of three shuttles ($N = 43$, Wilcoxon Rank Sum test).

Identification scenario	3 Shuttles				
NASA-TLX	M_{emp} (SD_{emp})	95 % CI [LL; UL][1]	M_{crit}	V^2	p^3
Mental demand	2.30 (1.26)	1.91; 2.69	< 5.00	3	< .001
Physical demand	1.26 (0.49)	1.10; 1.41	< 5.00	0	< .001
Temporal demand	1.88 (1.68)	1.37; 2.40	< 5.00	32	< .001
Performance	2.30 (2.58)	1.51; 3.10	< 5.00	149	< .001
Effort	1.67 (1.04)	1.35; 1.99	< 5.00	2	< .001
Frustration	1.77 (1.11)	1.43; 2.11	< 5.00	0	< .001
Total score	1.86 (0.82)	1.61; 2.11	< 5.00	0	< .001

[1] Confidence interval with lower (LL) and upper limits (UL).
[2] test statistic that indicates the sum of positive rank numbers.
[3] parameter p can only be estimated since ties exist in the data.

Table 7
Acceptance ratings of the vStop HMI after both shuttle identification trials ($N = 42$, Wilcoxon Rank Sum test).

Identification scenario UTAUT2 mod.	M_{emp} (SD_{emp})	95 % CI [LL; UL][1]	M_{crit}	V[2]	p[3]
Usability	5.43 (1.15)	5.07; 5.79	> 4.00	706.5	< .001
Intention to use total	4.64 (1.73)	4.11; 5.18	> 4.00	602.5	< .05
Total score	5.04 (1.26)	4.64; 5.43	> 4.00	734.5	< .001

[1] Confidence interval with lower (LL) and upper limits (UL).
[2] test statistic that indicates the sum of positive rank numbers.
[3] parameter p can only be estimated since ties exist in the data.

the threshold for positive evaluation significantly. Here, all contributing items were significantly higher than the 0.80 criterion, too. In terms of *hedonic quality*, the prototype showed rather neutral ratings. No item showed negative values.

4.4.5. Qualitative user feedback

The following subsection presents the qualitative user feedback regarding the vStop HMI prototype in the shuttle identification scenario. The AR information elements were very helpful for the participants to identify the SAV correctly. 14 participants explicitly highlighted usefulness of the stopping position element to prepare for boarding since it helps users to position themselves proactively. Including the conventional shuttle number was acknowledged by 19 participants as it allows for SAV identification without permanently holding up the device. In addition to the AR information elements, a conventional map was desired to show where the shuttle is coming from and how far it is ($n = 9$). Furthermore, higher contrast for the shuttle diamond element was mentioned to improve saliency against the blue-sky background ($n = 7$).

4.5. Discussion of the results of the second part of the user study

Participants had no difficulties with the task of correctly identifying the shuttle. As NASA-TLX total scores of both shuttle identification use cases showed low Cronbach's alpha values, interpretability was limited. In both identification trials, the TLX values were significantly below the self-established threshold of 5 (scale average) across all items. This indicates that the vStop HMI made it very easy for the participants to identify the correct shuttle. The use of AR enabled participants to spot the shuttle seamlessly, even among identical vehicles parking at the same stopping position. In fact, the almost identical TLX total scores for both use cases underline this finding. Consequently, the vStop HMI prototype could potentially assist users boarding the correct shuttle, regardless of situation complexity. As in the previous scenario, the *physical demand* item reflected mainly the interaction with the VR equipment. It was rated equally low across both identification trials, since the participants did not have to move at all this time. Also, *temporal demand* showed very low values as it was primarily an observational task. Participants did not have to take action beyond waiting for the shuttle and had no influence over the simulation of the scenario.

Table 8
User experience ratings of the vStop HMI after both shuttle identification trials ($N = 43$, Wilcoxon Rank Sum test).

Identification scenario UEQ-S	M_{emp} (SD_{emp})	95 % CI [LL; UL]	M_{crit}	V	p_{est}
Pragmatic quality	2.33 (0.73)	2.11; 2.56	> 0.80	939	< .001
Hedonic quality	0.94 (1.17)	0.58; 1.30	> 0.80	548	.184

[1]Confidence interval with lower (LL) and upper limits (UL).
[2]test statistic that indicates the sum of positive rank numbers.
[3]parameter p can only be estimated since ties exist in the data.

The significantly positive UX evaluation in terms of *pragmatic quality* reflected the vStop HMI's uncertainty-reducing character in this scenario. In contrast, the *hedonic quality* of UX was not significantly positive. Only the *usual/leading edge* item reached significantly positive scores (> 0.80), indicating that the participants value this new approach of using AR to identify the shuttle and stopping position. Overall, the UX evaluation results are consistent with those of the previous user journey scenario and provide valuable insights for the user-centered design process.

The acceptance rating of the vStop HMI for the identification task (measured with UTAUT2) was significantly positive. Surpassing the self-established threshold for both subscales (*usability* and *intention to use*) as well as the total score clearly highlighted the potential of the new concept. This suggests future adoption of such an HMI for these kinds of tasks. Especially in complex situations, users could make use of this concept as a fallback solution. Hence, this study demonstrated that shuttle identification can be considered another core task for the vStop HMI in the SAMOD user journey.

5. Synopsis of both parts of the user study

This research's results contribute to the user-centered design of a vStop HMI as well as the research fields of SAMOD and mobile AR. Furthermore, this work contributes to identifying valuable use cases for AR applications in traffic and mobility environments. Moreover, the results indicate the positive impact of a vStop HMI for SAMOD uses cases, suggesting that such new and sustainable transportation solutions could achieve market success.

In summary, the concept and proposed design appeared to address user needs in both investigated scenarios effectively. The baseline variant of the vStop HMI was characterized by very low cognitive workload ratings during navigation task. Furthermore, *pragmatic quality* was rated significantly positive during use, and acceptance was higher than the scale average for employing the concept to navigate to a vStop. In the first study, the treatment that restricted information access, intended to prevent users from constantly glancing at the device, provided an ambivalent result. On the one hand, the treatment did not affect the subjective ratings negatively, except for the workload in one navigation trial. The differences were significant, but not substantial. Accordingly, the overall workload for HMI with treatment was also rated at a low level. On the other hand, participants expressed their dislike for this type of treatment while simultaneously acknowledging its purpose of promoting user safety.

In the shuttle identification task, the vStop HMI also proved to be highly effective, regardless of scenario complexity. Hence, the conceptualization of the vStop HMI using AR was also successful and could provide additional value to future SAMOD users.

Taking both scenarios and user studies into account, the vStop HMI concept and AR technology proved to be consistently useful across contexts. The clear information presentation in the investigated user journey scenarios could help users seamlessly find their flexible pick-up location and booked SAV. This aspect may represent a crucial factor for supporting frictionless customer pick-up and pooled SAV operations, thereby positively influencing future SAMOD acceptance. Furthermore, this research identified the core features of the vStop HMI, namely effectively and efficiently highlighting relevant content in the real environment (i.e., vStop location and shuttle) by means of AR. Consequently, AR technology demonstrates a valuable use case within this proposed HMI concept. Especially in circumstances such as unfamiliar environments, stressful conditions, or first-use scenarios (where subjective task difficulty is likely to increase), the novel vStop HMI concept could be of significant value in future on-demand mobility user journeys.

5.1. Limitations

This explorative user study used a homogeneous sample of relatively young adults from an urban area with mid-to-high technology affinity and a comparatively high level of formal education. Such a composition is favorable for experimental UX studies to ensure coherent feedback within a specific user group and provide high internal reliability. However, a larger and more diverse sample could have produced stronger effects in the first scenario, particularly for NASA-TLX questionnaires.

Although no technical issues with the VR setup occurred, differences in participant's ability to operate the VR equipment may have influenced the study's internal reliability. The use of the HMD and controller in combination with the Cybershoes and the chair was new to all participants. Connecting the simulated smartphone to the controller made handling of the AR HMI relatively intuitive. However, moving with the Cybershoes remained an abstraction, and training was necessary. Some participants likely adapted more quickly than others. Another limitation of the VR setup was the need for adaptation to the VR environment. Since training in VR was required to establish consistent control of the equipment, all participants used the baseline HMI variant before the actual investigation. Consequently, those later assigned to group B also experienced the baseline condition. Hence, the evaluation of the information restriction condition was potentially influenced by prior exposure to the baseline. Throughout the investigation, the VR environment provided a standardized and highly controlled setup for the trial conditions, with identical stimuli for all participant and trials. The TUI questionnaire indicated good immersion rates. Still, some participants found it easier to adapt to VR than others. The instructor provided sufficient breaks and continuously monitored participant's well-being to prevent motion sickness. Nevertheless, one participant had to withdraw due to symptoms of motion sickness. Despite the breaks and the relatively short use cases, it is likely that some fatigue occurred toward the end of the study, which may have affected identification-task results. Because the user journey was presented chronologically, the order of scenarios was neither balanced nor randomized. As a result, engagement in providing feedback may have declined over time, potentially explaining the low Cronbach's alpha values for the TLX results in the second scenario. TLX results further suggested that the trials were relatively easy for the participants. Combining both scenarios into one extended trial might have increased task difficulty. Moreover, in the redirected navigation use case, questionnaire results indicate that HMI evaluation may have been biased toward the later part of the task (recency effect).

Since this explorative user study was conducted in VR, the external validity of the results is limited. The VR equipment enabled free movement and intuitive HMI use, yet handling, haptics, and interaction were inherently abstract and different to real-world settings. The VR environment simulated an existing intersection, enriched with vehicles and pedestrians to improve immersion, but could not replicate all aspects of a natural environment. Regarding HMI use, the simulated smartphone was intentionally scaled larger to ensure visibility, although actual device size in real world settings would differ. Conversely, VR provided a highly stable implementation of AR elements that would be challenging outdoors today. Even for moving objects, the digital AR information elements were perfectly aligned without drift. Lighting in VR ensured optimal visibility at all times. However, participants' behavior might differ in reality, where missing the shuttle and interaction with other road users could create more complexity and thereby alter the evaluation of the HMI.

It should also be noted that for NASA-TLX and UTAUT2, the researchers applied self-defined criteria for positive evaluation. Another factor limiting generalizability, particularly for acceptance ratings, might be social desirability. Despite the instructor emphasizing that there were no right or wrong answers, participants may have been reluctant to criticize the HMI prototype.

Finally, since this user study focused on evaluating the vStop HMI and the use of AR in two consecutive user journey scenarios, the underlying traffic coordinating and planning capabilities of the vStop concept itself were not included (Hub et al., 2023). Only the redirected navigation use case incorporated an aspect of this, by simulating a dynamic relocation of the pick-up position.

5.2. Future research

Further research should focus on investigating the UX of the HMI and the applied information restriction method with diverse user groups. Elderly individuals, children and people with disabilities could be of particular relevance. Designing and integrating group-specific features into the HMI should be targeted in subsequent user-centered design iterations. The same applies to the HMI used in the identification task. However, since shuttle identification was relatively simple in this study, future investigation should also include more complex scenarios. While the present investigation examined scenarios separately, future studies could integrate them into a single, uninterrupted trial with continuous tasks. This approach would help reveal potential blind spots in HMI support during transitions between consecutive user journey stages.

The present vStop HMI prototype relied primarily on the visual channel. Future prototype iterations could also incorporate additional sensory modalities. For example, integrating auditory of haptic feedback may enhance usability and reduce the risk of visual overload, resulting in a multimodal interface that could improve UX in the investigated scenarios. Moreover, further experimental studies could examine aspects of attention management and attention steering in AR-based interactions. In particular, situation awareness during vStop HMI use (in both variants) should be investigated, with a focus on traffic safety and the prevention of potentially dangerous situations. Accordingly, the vStop HMI and AR technology could be adapted to specifically address safety issues. Research should also examine which methods of regulating mobile AR use best support safe behavior in real-world contexts. Studies involving interaction with other traffic participants, such as cyclists, could generate important insights into preventing conflicts and increase safety in deployment

Building on this study, insights are needed regarding differences in information use between the HMI variants, especially when and where information was requested. Ultimately, the overall effectiveness of the vStop HMI and its distraction-prevention methods should be tested in real-world scenarios using extensive field studies. These studies could include objective measures of navigation and identification performance. Comparisons with other methods of information presentation and conventional interfaces (e.g., digital map navigation or market-ready AR apps) could also provide valuable benchmarks. Furthermore, context-adaptive vStop HMIs may enable task performance similar to always-on systems while promoting user autonomy, enhancing user experience, and reducing visual clutter. By tracking user's biophysical data during HMI use and adapting information presentation accordingly, intelligent features could be introduced to specific uncertainties in different scenarios. Such specific adaptations would require dedicated design iterations. Additionally, connecting the HMI with other smart traffic infrastructure elements or other connected road users should be explored. As AR capabilities advance, shuttle identification and long-route navigation under realistic outdoor conditions should become feasible. Future research must therefore examine AR interaction with moving objects in complex outdoor environments once the technology matures.

6. Conclusion

This research paper presents a prototypical concept for a vStop HMI designed to assist users in navigating to a flexible pick-up location and identifying their booked shuttle. The aim was to evaluate whether the vStop HMI has the potential to enhance the UX of SAMOD customers in two consecutive user journey scenarios and thereby support new forms of shared automated mobility services.

This explorative user study indicated that the differences in UX between the two investigated vStop HMI variants (information restriction treatment vs. baseline) were minimal in the navigation-to-pick-up scenario. Both HMIs were characterized by high rates of pragmatic quality, and acceptance as well as low cognitive workload. In the shuttle identification scenario, the vStop HMI prototype successfully met user needs for seamless identification, with all results indicating positive UX outcomes. The user study demonstrated that AR technology can effectively support users in navigating and identifying shared shuttles in future mobility contexts. Detecting, localizing and digitally highlighting specific points of interest (pick-up locations and shuttles) in the physical environment facilitated task performance and reduce uncertainty. Accordingly, the proposed vStop HMI design could become an essential component of future shared automated mobility services by efficiently providing customers with relevant information.

To translate these findings into practice, beyond operability, future development should consider partnerships with mobility service providers (e.g., Bolt, Uber, Waymo), smart city planners, and public transportation authorities to integrate the vStop HMI into real-world SAMOD pilot programs. Support by municipalities or government agencies to assure alignment with regulatory frameworks (i.e., data protection and safety) could play a decisive role for societal readiness. By enabling safe and more intuitive access to automated transit, the concept supports more efficient transportation ecosystems. Facilitating seamless passenger pick-up and shuttle pooling for a wide range of users could contribute to higher levels of public acceptance of automated urban mobility systems. In conclusion, the vStop HMI concept shows strong potential to improve UX in SAMOD user journeys and, in turn, contribute not only to technological innovation but also to sustainable, efficient, and socially beneficial transportation solutions.

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Institutional review board statement

The study was conducted in compliance with the Ethics Commission of the German Aerospace Center (DLR), letter of approval on the 15th march of 2023.

Informed consent statement

Informed consent was obtained from all subjects involved in the study.

CRediT authorship contribution statement

Fabian Hub: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Marc Wilbrink:** Writing – review & editing, Software, Resources, Methodology, Conceptualization. **Michael Oehl:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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