Introducing AV-Sketch: An Immersive Participatory Design Tool for Automated Vehicle — Passenger Interaction

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Fig. 1. AV-Sketch Interfaces: (a) a participant is manipulating 3D objects- stop button, visual display, weather/time icons in the VR scene (P5), (b) a participant is selecting auditory cues (P3), and (c) a participant is designing interfaces for the critical road scenarios with a warning symbol and placing the 3D element near the dashboard using the 'grab' feature of Quest hand tracking (P2).

In the emerging automated vehicle (AV) — passenger interaction domain, there is no agreed-upon set of methods to design early concepts. Non-designers may find it challenging to brainstorm interfaces for unfamiliar technology like AVs. Therefore, we explore using an immersive virtual environment to enable expert and non-expert designers to actively participate in the design phases. We built AV-Sketch, an *in-situ* (on-site) simulator that allows the creation of automotive interfaces while being immersed in VR depicting diverse AV-passenger interactions. At first, we conducted a participatory design study (N=15) by utilizing PICTIVE (Plastic Interface for Collaborative Technology) to conceptualize human-machine interfaces for AV passengers. The findings led to the design of AV-Sketch, which we tested in a design session (N=10), assessing users' design experiences. Overall, participants felt more engaged and confident with the in-situ experience, enabling better contextualization of design ideas in real-world scenarios, with improved spatial considerations and dynamic aspects of in-vehicle interfaces.

CCS Concepts: • **Human-centered computing → HCI design and evaluation methods**.

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1 INTRODUCTION

With the increasing prevalence of automated vehicles (AVs) in academia and industry [32], it becomes crucial to understand the needs and concerns of their passengers. The absence of a human driver to provide reassurance and guidance poses a significant challenge in ensuring proper communication between passengers and AVs [31]. As a result, passengers may feel less secure and exhibit a lack of trust in AVs' driving abilities [41]. A potential solution to this challenge is to design effective user interfaces (UIs) that facilitate better AV-passenger interaction. Specifically, UIs can be designed to provide passengers with a clear understanding of the AVs' actions and intentions [8, 9, 12, 44], which can help to build trust and confidence in the technology [39]. Previous studies have explored various UI designs for AVs, such as incorporating a driver avatar that mimics human behavior [24], an intelligent agent with personal traits [38], smart displays [3], and smartphone-based interfaces [36]. However, the quest for optimal AV-passenger interfaces is an ongoing research effort with numerous possibilities for improvement in usability aspects, effective information sharing, and ensuring perceived safety and acceptability [37]. As a result, researchers are exploring AV interface designs to enhance the user experience and interaction between passengers and AVs.

Understanding people's thinking and approach is crucial when designing a system for them [29]. To achieve this, the participatory design (PD) approach has been widely used in human-computer interaction (HCI) by engaging end-users in the design process [19]. In the automotive domain, past studies incorporated strategies and methods to conduct PD studies, such as PICTIVE (Plastic Interface for Collaborative Technology) [26, 31], co-designs [4], and user enactment [20] which facilitated the understanding of user and task requirements, and the design generation. In the PICTIVE method, participants engage in the ideation of design solutions incorporating paper-based sketching and/or low-fidelity prototyping. However, it can be challenging to ideate design interfaces for a new technology like AVs, which is not yet widely available in the market. Therefore, researchers rely on different media items such as images [5], video demonstrations [12], driving simulations [22], and proof-of-concept prototypes [26] to present the contexts of the study. While these methods can be effective in brainstorming the designed ideas, participants, especially non-designers, may struggle to envision and provide design insights for AV scenarios without prior experience with the technology [15].

Participatory design has been considered one of the most flexible design methods and allows combining other participatory approaches [23]. Virtual reality (VR), as technology, complements this method as it supports quick, relatively realistic, and safe demonstration of interface prototypes and presents scenarios in a real-world context. Recent works frequently use VR environments in the evaluation phase to test prototyped interfaces for AVs, and it is considered a beneficial medium to prototype and test simulations of initial designs [3, 13]. However, previous studies used VR mostly in the usability evaluation instead of the ideation phase, where most design creation and important decision-making takes place [17]. Therefore, we explored the integration of virtual reality in PD, allowing the participants to actively participate in the early design ideation phases through immersive experiences. Few other studies found the VR environment effective for allowing design collaboration by virtually connecting and engaging multiple participants in the urban design process [17, 28, 40]. Although these works employed VR in the design phases and

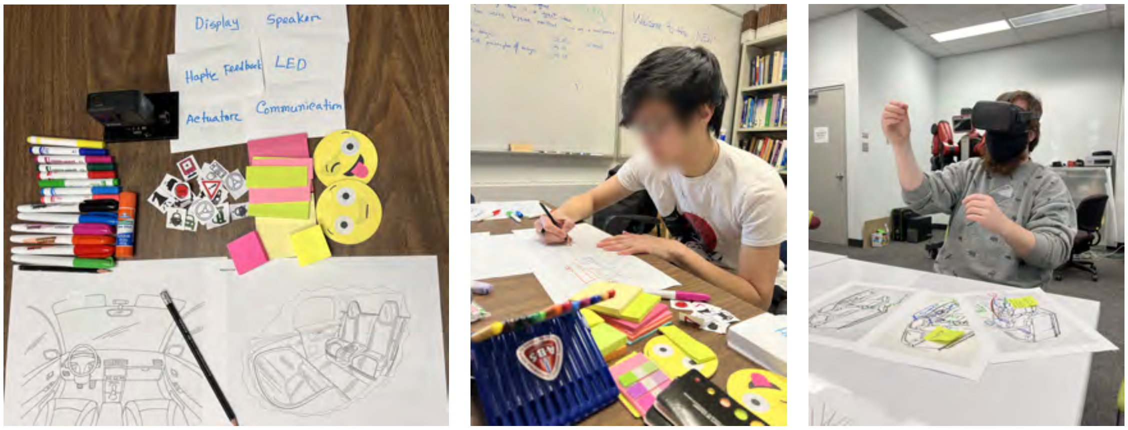

Fig. 2. PD study environment: (left) Setup elements for PICTIVE, (middle) The participants are sketching design ideas on initial sketches using the stationary items and supplied design icons for the stop button, emergency signal, display, etc., and (right) A participant is experiencing the AV-Sketch wearing the Meta Quest headset.

presented reflections on the deployment of VR in the early stages of product development for architectural 3D sketching and collaborative customization, it is still very much case-dependent [42]. Therefore, it is important to evaluate the usage of VR in the design phases for the automotive domain, which is still underexplored.

In this work, we built AV-Sketch, an *in-situ* (on-site) simulator that allows the creation of automotive UIs while being immersed in VR, depicting diverse AV-passenger interactions. At first, we conducted a PD study (N=15) by utilizing PICTIVE [35], an experimental brainstorming technique, to conceptualize human-machine interfaces for AV passengers. The findings led to the design of AV-Sketch, which we tested in a design session (N=10) and assessed users' design experiences. Our findings present user insights regarding both PICTIVE and AV-Sketch, highlighting AV-Sketch's effectiveness in creating realistic and enhanced design solutions.

Contribution Statement: Our research contributes (1) AV-Sketch as an open-source ideation tool, (2) in-depth insights into the contextual application of PD methods and VR sketching aligned with intended design objectives from two studies, and (3) new directions for future investigations in leveraging VR integration during ideation.

2 RELATED WORK

Various methods and techniques have been employed in the design and evaluation of automotive UIs, ranging from traditional paper-based design studies to AR/VR simulation for prototype evaluation [13]. Our research is grounded in two primary bodies of literature: 1) studies proposing AR/VR simulators for automotive UIs, and 2) scholarly research exploring VR as a tool in the design process.

2.1 AR/VR Simulators in Automotive Domain

Different studies utilized AR/VR platforms to test and evaluate proof-of-concepts for automotive UIs. Mahadevan et al. [30] prototyped interfaces in VR that contained LED strips, animated faces, and phone haptics and evaluated them in a user study. Another study [4] conducted co-design sessions online and developed potential interfaces in VR, where they found the VR testbed to be an important medium for running remote studies with an in-situ experience for participants. AR has been employed to visualize AVs' driving functionalities, including situation detection and maneuver planning, to investigate their impact on passengers' trust and acceptability of this technology [12]. Virtual reality driving simulators have been widely utilized in past studies to assess various aspects of automation within a risk-free environment. Yeo et al. [46] evaluated six different driving simulators with varying visual and motion configurations, where they utilized mixed reality for lab-simulated and real-world driving simulators. Another study [21] introduced "XR-OOM," a mixed-reality simulator where participants can experience virtual object overlays in a real-world driving environment. While these simulators are effective for testing user interactions in automotive research, our proposed AV-Sktech tool will facilitate initial design iterations within VR before moving to the testing phase of in-vehicle UIs.

2.2 Virtual Reality in Participatory Design

Previous research has predominantly employed VR as a design tool in areas such as architectural design, urban planning, collaborative 3D sketching, and gaming. Schnabel et al. [40] utilized VR as a participatory design tool, engaging participants in urban design within a simulated environment. This allowed for 3D object manipulation, including the design of building shapes, forms, and their positioning in real-world contexts. Similarly, another study [17] applied the co-design method in VR, fostering collaboration among designers through 3D sketching. Participants generated 3D sketches and virtual models for various spaces, supporting user empowerment via VR design experiences with visualization and verbal exchanges. Additionally, Hyve-3D, introduced by Dorta et al. [16], facilitated architectural co-design in VR. Designers interacted with the simulated environment using a 3D cursor via a handheld tablet. Finally, Mei et al. [34] investigated the utilization of VR as a cake customization tool, allowing clients and chefs to design their desired cakes collaboratively. Their CakeVR tool supports various features, including design choices, color/flavor selection, decorations, customization, and remote ideation of cake designs. While these studies have utilized VR as a design tool across various domains, there has been a lack of exploration in the automotive domain. Therefore, we explore the integration of VR with the traditional PD approach to generate more mature and improved design solutions.

3 METHODOLOGY: PARTICIPATORY DESIGN STUDY

We conducted individual PD studies with N=15 participants, where they designed interfaces for passengers to interact with AVs. We applied PICTIVE as a traditional PD method [35], allowing participants to express their initial ideas visually by sketching, adding labels, and creating low-fidelity prototypes. Therefore, we selected it as our PD method like prior research [2, 31] to actively engage participants and facilitate the generation of interfaces for AV-passenger communication. The findings from this phase have been utilized in designing AV-Sketch, the VR simulator tool.

3.1 Participants

We recruited 15 participants (6 female, 9 male) aged 20 to 35 years (M=25, SD=4.25). Seven participants were interaction designers with an average of 2 years of experience (SD=1.4); others self-identified as novice designers. We intentionally included participants with different design backgrounds to explore variations in their involvement and design strategies within the presented methodology. Participants with design expertise were recruited from the university's design and HCI lab, while others were identified through snowball sampling and direct emails.

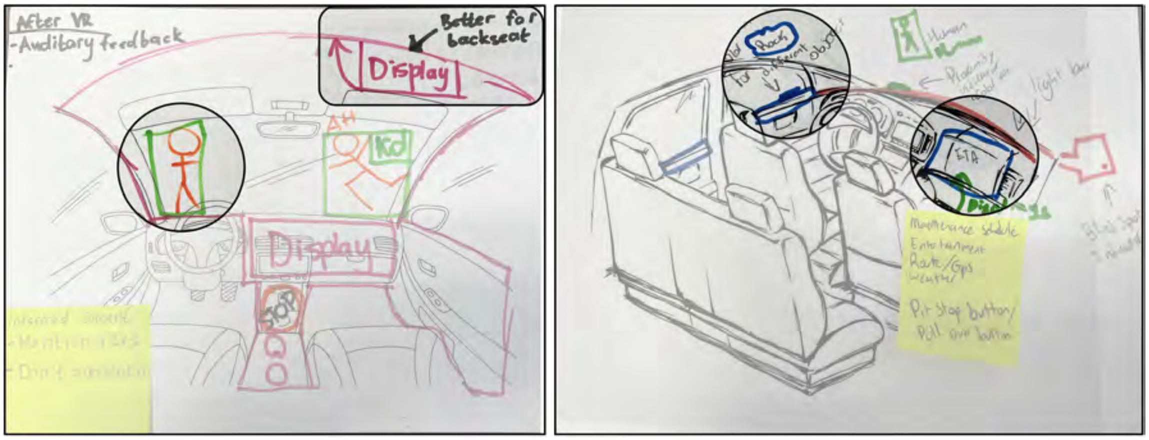

Fig. 3. Participants' created example sketches: (left) showing a pedestrian symbol to project on the windshield when a passenger is crossing the street, and multiple displays to enhance visibility for passengers seated in the rear of the vehicle; (right) showing a display with navigation placed near the dashboard and LEDs placed on the side window.

3.2 Study Procedure

All sessions were conducted by the first author in a lab-simulated environment. First, we provided a brief introduction to our research and explained the study's procedure. After obtaining participants' consent, we collected demographic information. By adopting the PICTIVE method (see Figure 2 (middle)), we followed traditional paper sketching to brainstorm and ideate interfaces. We provided design sheets with three initial sketches of the vehicle's interior (two traditional vehicle interiors and one Waymo vehicle interior [1]. Participants were also given different design icons like stop buttons, emergency signals, and displays (see Figure 2 (left)). These items were used to facilitate interface creation and help prompt design ideas. We allowed participants to use any presented labels, such as speaker, haptic feedback, and communication, or define their own. We also supplied stationery items like colored pens, pencils, and sticky notes for sketching. Additionally, we presented videos and images featuring conceptual AV models to acquaint participants with the concept of automated vehicles.

For the ideation, participants were presented with scenarios to map a passenger's journey in an AV: 1) entering an AV and starting for the destination; the vehicle performs regular driving tasks such as lane changing and stopping before the crosswalk, 2) riding inside the AV in regular traffic, heavy traffic, and in extreme weather (e.g., fog [45], snow, rain) [3]. All participants were encouraged to discuss their designs and considerations through a think-aloud protocol [27]. The design activities lasted approx. 60 min. Finally, we ended the session with an open-ended discussion to gather participants' opinions on their experience with PICTIVE. Each session lasted approximately 90 minutes. Participants received compensation of $15 CAD Amazon gift cards. All sessions were video-recorded with the participants' permission for further analysis. The study setup is shown in Figure 2 (left).

3.3 Data Sources and Analysis

We collected pictures of the participant-created sketches (25 unique drawings) and video recordings of the study sessions. Afterward, we transcribed the relevant conversations from the recordings of all sessions. With the transcribed data and co-designed sketches, we proceeded with open coding (performed by two authors) to identify codes [14]. Some example

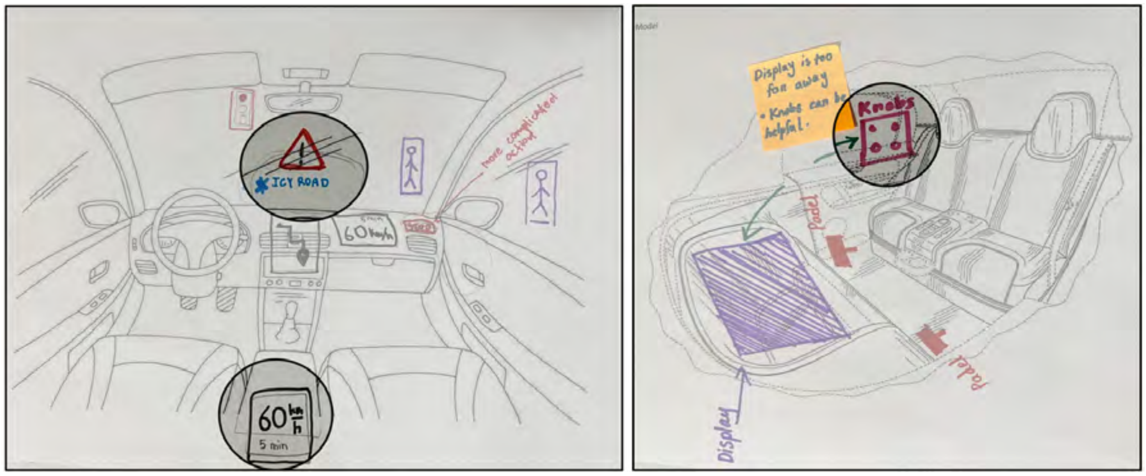

Fig. 4. Participants' created example sketches: (left) showing initial designs on the windshield and on a display positioned in the middle of the front seats for better access of the backseat passengers; (right) showing designs on the Waymo vehicle model where the control knobs of the displays are placed near the seat considering how far the displays are from the passengers.

codes are cue location, modality, display information, audio commands, navigation, emergency buttons, sketching tools, design generation, etc. We iteratively refined the codes via discussion before clustering related codes into patterns that represent our findings on the design of AV interfaces and observations on the PD method.

3.4 Findings

This section presents the design findings to facilitate easy communication for passengers with AVs and reflects on the observations of the PD experiences of the participants utilizing PICTIVE.

3.4.1 Design Interfaces for AV-Passenger Communication. We received designs that considered the AV's ability to convey its intentions and awareness of the surrounding traffic environment. All participants mentioned receiving some information like weather, speed, and traffic from the vehicle utilizing multi-modal (visual, auditory, and haptic) communication. P12 highlighted this saying, *"It would be better if the vehicle is showing what I am seeing."* Proposed design solutions (22 out of 25 drawings) frequently featured dynamic displays for presenting information like speed, navigation, and traffic notifications. 10 out of 15 participants preferred to have auditory cues to communicate route details and alerts upon reaching the destination. However, in specific situations like commencing a journey, navigating through extreme weather conditions, or stopping for pedestrians, 16 designs featured a combination of both auditory and visual feedback, and 5 designs incorporated haptic feedback.

Most designs featured user interface elements like emergency icons (18 designs) and high-contrast colors (15 designs) to reflect urgency. Along with digital interface elements such as LCD displays and LEDs on the side windows or windshields (see Figure 3 (right)), some designs also incorporated the existing manual features in vehicles such as knobs, stop button, and emergency brake pedal (see Figure 4 (right)). Thus, it can be implied that participants utilized their familiarity and experience with traditional vehicles when creating interfaces. The participants considered the location for placing the interface elements to make it easily accessible for all the passengers. Seventeen designs utilized the windshield space to display visual cues in their designs, and others mainly considered the traditional locations near the dashboard (see Figure 3 (right)). However, most participants struggled to determine the ideal placement of the stop button, as this can be pressed accidentally. Six participants suggested adding unique steps/covers before activating the button. Also, 8 (out of 15; 53.33%) participants brainstormed to explore potentially better locations of interface placement for the backseat passengers (see Figure 3 (left)).

3.4.2 Observations on Participatory Design with PICTIVE. According to participants, the PICTIVE design method facilitated idea generation with flexibility and helped them visually present the initial metal images of the design ideas. Four (out of 7) interaction designers with previous design expertise in the AV domain captured the concepts relatively quickly and showed confidence in creating design sketches. However, for some novice designers (N=5), actively engaging in the PICTIVE design process presented challenges in visualizing interactions with novel concepts like AVs. They showed a preference for describing design ideas verbally rather than resorting to sketching, considering verbal commands as an easy medium to express ideas. P13 mentioned, *"PICTIVE provided more freedom and options, but it was still harder to come up with ideas on your own, and having too many options can create cognitive load."* During the design task, 11 out of 15 (73.33%) participants encountered this hurdle, particularly with the Waymo vehicle design sketch. The Waymo model, being a novel concept with no traditional driving wheel and a unique interior, posed difficulty in understanding the interior space and the placement of elements (see Figure 4 (right)) for an illustration of a participant's confusion about the distance between the user and the screen, leading them to design the control knob near the windows for easy access to display functions). Additionally, participants required more time while sketching for the Waymo design, and some (8 out of 15; 53.33%) preferred to design only on the traditional layouts. Three participants mentioned the challenge of drawing on the given sketch; P5 emphasized it, saying, *"I was struggling to draw utilizing the same space of the layouts, I would rather prefer blank sheets."*

4 DESIGN & IMPLEMENTATION: AV-SKETCH

In our design study, we investigated how participants utilized PICTIVE, a popular PD method, during the brainstorming and design of AV interfaces for specific scenarios outlined in Section 3. We identified various challenges associated with paper-based design studies in generating realistic interface ideas, including envisioning scenarios with new technology, feeling comfortable sketching, and effectively using provided materials. Such obstacles diminish user involvement and active participation in the early design phases. Therefore, our proposed tool, AV-Sketch, addresses these challenges by facilitating the creation of automotive interfaces with immersive experiences. It allows participants to interact with and modify objects within a 3D environment (see Figure 1), thereby transforming initial sketches obtained from the PICTIVE method into more refined designs with spatial precision.

Different design factors, stemming from the findings of the initial design study, were considered for the design of AV-Sketch, ranging from design environment, choice of 3D elements, object manipulation features, and adaptability of the tool for both expert and non-expert designers.

4.1 Immersive Environment & VR Scenarios

We implemented three scenes depicting the same two scenarios from the design sessions in VR using Unity3D 2018.4.14. Participants acted out predefined scenarios as passengers wearing a Meta Quest 2. In the scenes, we used two vehicle models (similar to the provided sketches in PICTIVE) to gather participants' opinions on different interior designs. For the first scene, we used a Google Waymo [1] vehicle model (no steering wheel), while in the other scenes, we used a traditional vehicle model with a steering wheel, resembling a Toyota. We designed a homepage with menu items where participants can activate each scene. After experiencing a scene, participants enter the design scene for that specific scenario. During initial testing, the AV is in motion, and participants remain seated, observing the AV's driving and surroundings. Designing in a moving scene can be distracting for design activities and may induce simulation sickness. Therefore, in the design scene, the AV remains stationary and parked in a specific spot, allowing participants to focus properly.

In all the scenarios, the vehicle travels from point A to B and performs various driving tasks, such as changing lanes and stopping before a 'stop' sign and a crosswalk. The scenes depict an urban environment with other vehicles, pedestrians walking and crossing streets, and children playing (see Colley et al. [11]). We considered multiple factors for the simulation design, including vehicle design, speed change in heavy traffic, traffic environment, and visual appearance of the environment, like changing the scene's lighting to simulate foggy weather. The scenes did not include interface elements to let participants engage in the actual scenarios and perform design activities without biases.

- **Scene 1:** Riding inside an AV to a destination in regular traffic (regular number of vehicles). The AV drives in the left lane, changes the lane in the middle, and then stops before a crosswalk. Before the vehicle entirely stops at the crosswalk, a child unexpectedly starts running to cross the street (see [11]). We designed this plot to observe the participant's reaction and interaction with AVs during a sudden incident. (Waymo, front-seat view)
- **Scene 2:** Riding inside an AV in heavy traffic (congested roads with other vehicles). The AV drives slowly and stops at a 'stop' sign. (Traditional vehicle, back-seat view)
- **Scene 3:** Riding inside an AV in foggy weather conditions. The vehicle drives in the left lane and then stops at a 'stop' sign. (Traditional vehicle, back-seat view)

4.2 Design Elements and 3D Manipulation

Each scene incorporates pre-designed 3D elements selected based on the most popular and preferred elements from the participants' initial PD phases (see Section 3.4). Visual displays, maps, and icons for general information like weather, time, and speed are included in all scenes as they were commonly used in participants' designs. Some elements, such as pedestrian walk symbols, animated walks, emergency symbols, and stop buttons, are also designed as scene-specific elements. We incorporated verbal commands as auditory cues. Examples are- "Welcome to your ride, your destination is XYZ," (scene 1), "Starting for the destination," "Stopping for the pedestrian" (scene 2), and 'Heavy traffic on the road' for scene 3. Participants can combine these interface cues according to their design ideas.

AV-Sketch enables participants to manipulate the presence and position of 3D elements within the VR environment. They can design interfaces from pre-defined interface cues using the Grab feature provided by the Meta Quest hand-tracking. For example, to illustrate pedestrian detection by the vehicle, participants can select from three different cues: a dynamic display showing pedestrian progress, a pedestrian symbol (see Figure 5 (a)), and/or verbal commands found most common in the early designs from our PD phase. Participants benefit from situated experience and can move around the scene to design interface cues from different passenger seating positions (e.g., front seat, back seat passengers). Secondly, they can also consider adjustments in size (resizing) and intensity (visual properties such as transparency to high contrast) for the 3D cues while positioning the interfaces within the context of the vehicle's size and seating positions. To elevate the overall sense of modality, we retained both auditory and visual cues in the pre-defined interfaces. Additionally, participants can choose the voice for auditory commands (see Figure 1 (b)), including options for both male and female voices.

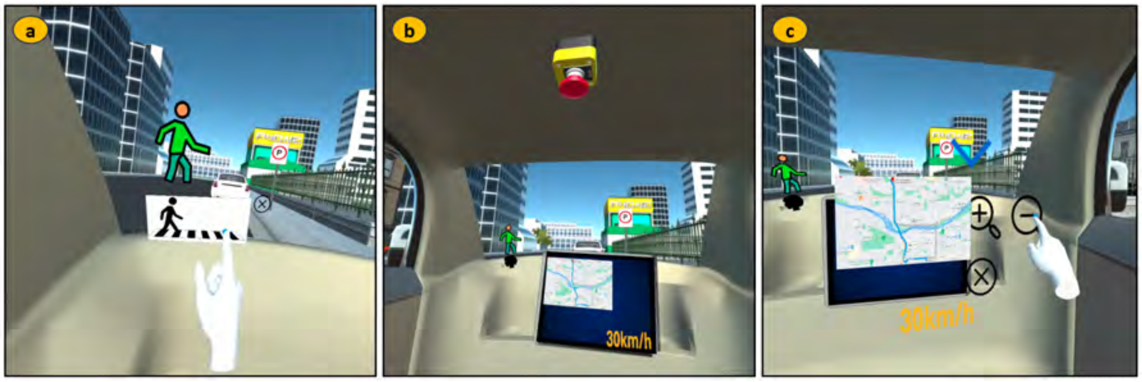

Fig. 5. AV-Sketch Interfaces: (a) a participant is selecting from multiple pedestrian symbols (P7), (b) the stop button is positioned on the ceiling of the vehicle to prevent accidental presses (P4), and (c) a participant is resizing the 3d display (P10).

4.3 Adaptability & Familiarity

To familiarize participants with AV-Sketch, we included audio narratives explaining the tool's components and how to navigate its features. This approach significantly reduces the reliance on study facilitators to guide participants. Such guidance can disrupt the immersive experience, as it may require participants to remove the headset or communicate verbally with the facilitator. Recognizing the intuitive nature of using one's hands in design activities, we incorporated hand-tracking features from the Meta Quest. This allows participants to interact with and manipulate objects within the VR environment using their hands instead of traditional controllers. After completing the design for one scene, participants can easily transition to designing the next scene from the main menu. Participants often try the same scene multiple times, allowing for redesign and incorporation of new ideas.

5 METHODOLOGY: AV-SKETCH DESIGN STUDY

To evaluate the effectiveness of AV-Sketch as a tool for reiterating and generating early design concepts, we invited 10 participants (*N*=6 designers; 4 females, 6 males) to participate in the second design study who also participated in the first study. The first author conducted these sessions in a university lab setting, and the study was approved by the author's university's Ethics Review Committee.

5.1 Study Procedure

Initially, we introduced our objectives and explained the study's procedures to the participants. Consent forms were distributed, and participants were asked for their approval to take part in the study. We provided a brief orientation to the participants regarding the Meta Quest headset using a test scenario. This scenario placed the participant in a static vehicle parked on the curbside, where they could enter inside the vehicle and use hand gestures to interact with randomly selected 3D items (not used in the actual scene). Once participants were comfortable with the interface and navigation, we commenced with the actual VR scene and enabled casting, allowing the facilitator to monitor and interact with participants. Participants were asked to test the VR scenarios first (see Figure 2 (right)) and then design interfaces for each scene utilizing the AV-Sketch's pre-defined 3D elements. While designing, participants were encouraged to explain their design rationale aloud. Participants remained seated throughout the experiment, positioned inside the simulated vehicle in VR while playing the role of passengers. The VR setup process took $\approx$ 10 minutes, although participants with prior VR experience required less time. To assess the simulation sickness in VR, we utilized a single-item misery scale [6].

After completing the design task, we conducted an open-ended discussion to gather participants' opinions on the immersive design activities in AV-Sketch. We asked questions to obtain a holistic perspective on both studies (PD and AV-Sketch). Some example questions included: 1) How did AV-Sketch assist you in generating the design interfaces?; 2) What techniques or methods were most effective in inspiring and generating your design ideas?; 3) What differences did you notice while trying both ways of brainstorming and creating designs?; and 4) What are some key benefits and drawbacks of each design methodology you have used?. We concluded the session by administering a post-study questionnaire to collect participants' responses. The questionnaire included multiple quantitative statements aimed at comparing participants' experiences in the design studies with PD and AV-Sketch. Participants rated their agreement with six statements using a 5-point Likert scale (1=Strongly disagree to 5=Strongly agree) for each method. The statements were as follows: S1) "The method supports creative practices"; S2) "The method supports flexible design activities; S3) The method is easy to incorporate in the design ideation"; S4) "The method is helpful for quick design generation"; S5) "The method supports realistic design creation; and S6) The method supports active user involvement/participation". These statements are adapted from the Creativity Support Index (CSI) [7] as the evaluated design methods are part of creativity support tools. We focused on three specific factors from the CSI, exploration, expressiveness, and immersion, considering these to be more relevant in evaluating the creative experiences of participants using the PD method and the proposed AV-Sketch design tool as a proof-of-concept prototype.

Each session lasted around 75 minutes, and participants received compensation in the form of $15 CAD Amazon gift cards. With participants' permission, all sessions were video-recorded. Additionally, the design activities within the VR environment were recorded through the headset, producing 3D sketches that were collected as the study output. The recordings were transcribed, and we used open coding [14] to analyze the qualitative data. Then, we performed the Wilcoxon Signed-Rank Test on the quantitative data (alpha level=0.05), considering the small sample size to report the statistical significance between the PD method with PICTIVE and AV-Sketch.

5.2 Findings

This section highlights participants' design experiences in the immersive AV-Sketch tool and presents a comparative analysis of the two studies utilizing PICTIVE and AV-Sketch.

5.2.1 VR Scenarios and In-situ Experiences. The VR simulations gave participants an immersive view of the AV's surroundings, street objects, and actions, enhancing the realism of the scenarios. Most participants (9 out of 10) reported that the integration of VR in the design process aided them in iterating their designs with improved space perception and finer details. For example, initially, participants placed most of the interface elements on the windshields but later considered alternative locations to avoid visual clutter (see Figure 4 (left)). As participants were primarily focused on observing how AVs operated, they desired an unobstructed view of the external environment. Six participants preferred to have a user customization option to set preferences for choosing different cues' locations, frequency, and modality. However, integrating VR simulations presented certain challenges, as noted by most participants. P10 mentioned, *"I got involved in observing different factors, such as how the vehicle was driving and communicating with the traffic surroundings. Suddenly, I realized I wasn't thinking about the design!"*

Consequently, many participants revisited the same scene to rethink design aspects during the stationary design task in the AV-Sketch tool. They acknowledged that VR immersion inspired new ideas by offering a detailed representation of a full passenger journey, a dimension not fully captured during the initial design session. Surprisingly, many participants (7 out of 10) mentioned that they would not require as many interfaces as they initially designed to communicate with the vehicle after observing how the AV acted in different scenarios. We inferred that participants felt safe and trusted in the AV, as the driving style with proper speed changes served as implicit cues. Additionally, scenes featuring the traditional vehicle with steering wheels sparked discussions regarding participants' opinions on the future layout of AVs. While 6 participants preferred the steering wheel, others favored the Waymo vehicle, which reflects the fully autonomous level of vehicles. P3 noted, *"Not seeing anyone in the driving seat with the steering wheel felt so different when I tried the scenes. But, it should be here at least for the transition period of AV acceptance, as it gives a sense of control in emergencies."*

5.2.2 Design Activities in AV-Sketch. Some participants in the PD study mentioned a preference for both auditory and visual cues in certain scenarios, such as when a pedestrian is crossing. However, most participants (7 out of 10) chose to have only visual cues, as having both modalities overwhelmed some (4 participants) upon testing with AV-Sketch after having a better sense of modality (visual and auditory). In Figure 3 (left), we can see participants drew large-sized pedestrian cues over the windshield, which demonstrates the missing precision in paper sketching. AV-Sketch enriched participants' understanding of item localization, including where to place elements, and an appreciation of positioning, size, and spatial occupancy within the vehicle. See Figure 5(c), where the participant is interacting with a display to resize it to match the vehicle's internal space. Among the 10 participants, seven explored new locations, such as corners near the windows and ceiling within the 3D vehicle model. For instance, they positioned the emergency button on the ceiling to prevent accidental pressing (see Figure 5 (b)). Six participants designed interfaces specifically for backseat users with limited visibility of the windshield and placed separate displays in the rear (see Figure 1(a)). Others positioned elements in the middle of the front seats, making them accessible to backseat passengers, similar to the initial sketches of PD design (see Figure 4 (left)).

5.2.3 Comparative Findings on PICTIVE and AV-Sketch. From the evaluation of AV-Sketch, we found that this VR tool enabled participants to re-imagine their initial design interfaces in the first study for various AV-passenger scenarios with enhanced precision and spatial understanding. During the PICTIVE design phase, participants expressed difficulties (S3: M=3.1, SD=1.20) in sketching using the Waymo AV model. However, once they had the opportunity to experience it within a 3D environment, the localization and perception challenges were largely overcome. Likewise, these issues were not observed during the AV-Sketch sessions, where participants could realistically picture the scenario and better understand the environment while being situated in the immersive space (S5: M=4.1, SD=0.74; W=2.5, p=.02, r=0.79). This also increased the active involvement during the design process via the AV-Sketch tool (S6: M=4.5, SD=0.71) compared to PICTIVE (S6: M=3.4, SD=0.97). A Wilcoxon Signed-Rank test indicated a statistically significant difference between the scores, W=0, p=.02, with a large effect size (r=0.89).

We observed some other comparative analyses of the PD and AV-Sketch methods from the Likert scale questions. Eight out of ten participants found AV-Sketch effective for generating quick designs (S4: M=4, SD=0.63), compared to PICTIVE (S4: M=3.2, SD=1.23), W=4.5, p=.03, r=.71. One participant (P4) expressed, *"I liked that you get to visualize the interaction in a real-world context and quickly design from the given elements, which made me confident in presenting my interface ideas better."* The PD method with PICTIVE received higher scores as a creative design approach for initial idea generation (S1: M=3.9, SD=1.04) and for its flexibility (S2: M=3.7, SD=0.95) in brainstorming with freehand sketching. However, AV-Sketch was found to be limited in providing flexibility (S2: M=2.9, SD=0.88) and creativity (S1: M=2.4, SD=0.94) due to the pre-defined 3D interface elements. A Wilcoxon Signed-Rank test revealed the statistical significance between PD and AV-Sketch in terms of creativity (W=3, p=.02, r=0.77), while no statistical difference was found for flexibility (W=2, p=.07, r=0.73). Moreover, three participants rated AV-Sketch a 4 out of 5 for its flexibility in offering customizability features, such as resizing, modifying, and moving objects within the space. Overall, participants considered AV-Sketch as a valuable prototyping tool for refining and validating early design concepts generated during brainstorming sessions. P7 noted, *"It was an opportunity to verify and fine-tune the ideas. I can see its benefits as a second layer for design iterations before finalizing the solutions!"*

6 DISCUSSION

We reflect on the research methods emulated in different study phases- PD with PICTIVE and 'AV-Sketch' as an immersive VR tool to optimize early prototyping. Our findings highlight PICTIVE as a creative and flexible ideation tool, while VR serves as both a validating tool and a secondary layer for design iterations.

Reflection on the Design Methods

Each method, PD with PICTIVE and AV-Sketch, has its unique set of advantages and drawbacks. PICTIVE sessions were effective in fostering productive brainstorming sessions marked by lively discussions which align with past studies [26, 31]. These sessions encouraged creativity without imposing constraints on the design possibilities. However, they fell short in providing the necessary contextual information, especially for emerging technologies like AVs. Structured design elements and specific details, crucial for interaction sequences and placement, were lacking, making it challenging for both designers and non-designers to visualize complex scenarios and dynamic aspects inherent to AV interactions. During the study sessions, we observed that participants encountered difficulties, mainly when dealing with the Waymo vehicle design sketches, which presented a departure from the traditional vehicle model. Given their lack of prior experience riding in such a vehicle model, participants struggled to envision the interface designs.

AV-Sketch with VR simulations offered a more immersive and contextualized design experience. Immersing participants in the dynamics of a passenger journey in AVs enhanced their understanding of how interfaces would function within various scenarios. This was particularly effective in sparking innovative ideas and refining initial sketches as highlighted in prior research [16, 17]. It streamlined the generation of precise and relevant interface concepts, prompting a focus on essential cues. Nevertheless, there were challenges associated with AV-Sketch's lack of flexibility and scalability. There was limited control over modifying the physical environment within VR to generate design concepts. Overall, a combination of both methods proved valuable in different aspects of the design process supporting early design creation.

AV-Sketch– In-situ Design Tool to Support Optimized Prototyping

AV-Sketch is a promising tool for supporting prototyping in the context of AV-passenger interaction design. One of its notable strengths is its capacity to bridge the gap between ideation and precision in interface design. Through the immersive VR environment, AV-Sketch allows participants to move beyond mere sketches and conceptualize interface elements within the spatial context of an AV. This feature fosters better spatial recognition, a key facet in designing interfaces for complex in-vehicle scenarios [46]. The tool's pre-defined 3D elements enable rapid selection and placement, expediting the design process. This feature aligns with the advantages of VR design tools highlighted in other works focusing on urban design [40] and collaborative customization [34]. Furthermore, AV-Sketch accommodates both auditory and visual cues, catering to varying design preferences. While participants with design expertise appreciated the customizability features- resize, visual intensity setting, and modality choice, even those without a design background found it instrumental in translating their ideas into concrete designs. Overall, AV-Sketch encourages designers to think beyond the 2D realm, offering an efficient means to materialize early design concepts.

AV-Sketch– Potential Bias and Future Opportunities

The use of AV-Sketch has its own set of limitations and future opportunities. One key limitation observed during the experiments was the potential bias introduced by pre-defined design elements in the VR environment. Participants often gravitated towards these suggested tools, limiting their freedom to explore entirely novel design ideas. However, it aligned with our design goal of optimizing/refining the initial sketches generated from the PD method through paper sketching. To increase the scope of AV-Sketch in future designs, participants expressed the desire for features like free-hand sketching in VR, which could enable a broader range of design possibilities as shown in Drey et al.'s work [18]. Moreover, future design should consider enhancing customization options, including an immersive editing environment with a wider variety of 3D elements and access to a comprehensive dataset of elements. This expansion of capabilities would empower designers to think more creatively and not be confined to a limited set of pre-determined elements.

Another exciting opportunity for AV-Sketch is enabling collaborative design within the VR environment, even remotely. Collaborative design in VR showed promise in previous research and can strengthen the ideation process. Allowing co-designers to work together in a shared immersive environment can facilitate real-time brainstorming and idea exchange, leading to richer and more innovative design concepts [17, 28]. This collaborative aspect could be a valuable addition to AV-Sketch, enabling design teams to co-create and refine interfaces more effectively. Finally, immersion could be increased via approaches like XR-OOM [21], PassengXR [33], SwiVR-Car-Seat [10], or VAMPIRE [25]. The SwiVR-Car-Seat and VAMPIRE integrated rotations and kinaesthetic feedback to simulate vehicle motion, enhancing perceived realism in automated VR driving simulators. These innovative solutions could complement the AV-Sketch design study, enhancing participants' experience by simulating real-world driving motion.

Limitations

As an initial exploration of the AV-Sketch design tool, our study is subject to several limitations. Firstly, the study's sample size was small to medium, raising questions about the generalizability of our findings. However, the qualitative open-ended discussion allowed us to gather detailed insights, enhancing the validity of our results [43]. Additionally, due to the scope of the study, we had to constrain the variation of scenarios and interface elements tested in our implemented simulation. Nonetheless, our implemented design tool with commonly preferred 3D elements served as a proof-of-concept evaluation. Future research should explore more diverse and critical scenarios (e.g., extreme weather conditions, near-crash events) with a broader range of pre-defined/customized 3D elements and gather feedback from many participants on an updated version of the design tool. Despite these limitations, our work offers preliminary insights into utilizing AV-Sketch/VR as a design tool in the automotive domain, advancing the state-of-the-art substantially.

7 CONCLUSION

We present AV-Sketch, a VR tool designed for AV-passenger interaction. AV-Sketch empowers designers and novices to brainstorm automotive UIs, fostering the development of refined interfaces within the iterative design process.

Our findings revealed that participants exhibited higher levels of engagement and self-assurance when utilizing AV-Sketch's in-situ approach. This approach enabled them to contextualize their design concepts within real-world settings more effectively, taking into account spatial and dynamic elements of in-vehicle UIs. With the growing demand for personalized design solutions, AV-Sketch offers an open-source and inclusive tool to improve automotive UIs.

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