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Collaborative Experience Prototyping of Automotive Interior in VR with 3D Sketching and Haptic Helpers

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ABSTRACT
Technological advances and socioeconomic disruptions such as self-driving cars, car-sharing services and artificial intelligence assistance may fundamentally alter interactions inside the future car. However, existing design tools and processes geared toward static physical authoring are ill-equipped for such interaction design. We propose a new design workflow that combines experience prototyping methods typically used by the user interface and product design communities with 3D sketching and haptic helper techniques to help automotive designers ideate, prototype, experience and evaluate multi-sensory interactions in a collaborative manner. Using our workflow, designers use 3D sketching to quickly and expressively author 3D shape and motion ideas in space; augment them with tactile and other sensory feedback through physical proxies and other available gadgets; and immediately enact and immersively experience them to progressively explore and develop them.

Author Keywords
Automotive design; experience prototyping; design methodology; 3D sketching; haptic feedback; virtual reality

CCS Concepts
- **Human-centered computing~Collaborative content creation**
- **Human-centered computing~Interactive systems and tools**
- **Human-centered computing~Virtual reality**

INTRODUCTION
Recent progress in various automotive technologies such as self-driving cars and socioeconomic disruptions such as ride-sharing services may fundamentally alter the activities in which drivers and passengers inside a future car will be engaged. For instance, drivers will no longer be required to pay attention to the road, thus having more time for work, entertainment and other meaningful activities.

Such a transformation requires a radical rethinking of the car interior, incorporating a higher degree of interaction with a wide array of interior components through UI techniques such as gesture [39, 56], voice and gaze input [39], head-up display [7], tactile feedback [47] and even holograms [14].

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Figure 1. In our workflow, designers express ideas with 3D sketching and immersively experience them in VR with physical proxies. By prototyping and experiencing together, designers collaboratively develop future automotive interiors.

A redesign of this magnitude would hugely benefit from *design thinking* [38] that entails rapid ideation, prototyping, experiencing and evaluation of possible interaction ideas. Through this process, automotive designers can attain hands-on understanding of the possibilities, from which to identify promising directions and draw further inspiration [9].

Traditionally, for designers to step inside a concept interior, gain a realistic sense of it, share perspectives and collaboratively evaluate it, a 1:1 physical model is created [22, 54]. The physical mockup, however, is expensive and slow to construct and mostly static, limiting the designers’ ability to ideate, prototype, experience and evaluate the future interactions, especially during the early design stage.

In this paper, we propose a workflow for designing future automotive interior: *Collaborative Experience Prototyping in VR with 3D Sketching and Haptic Helpers* (CEPVR). Using CEPVR, designers can inexpensively and flexibly ideate, prototype, experience and evaluate rich interactions in a collaborative manner, with suitable fidelity (Figure 1).

In the next section, we summarize previous works on VR modelling and 3D sketching. Based on analysis of existing prototyping methods and a formative study, we formulate goals and directions of a new workflow, CEPVR. We then conduct a user test, discuss findings and draw conclusions.

RELATED WORK

In this section, we summarize previous studies on the use of VR in the design process, 3D sketching, haptic helpers and existing experience prototyping methods used in UI design with regard to automotive interior interaction design.

Applying VR to the Design Process

VR's ability to provide a high-fidelity visual experience for the wearer makes it a potent tool in the design field [6, 20]. There have been many attempts to incorporate VR into automotive design, where a 1:1 physical model of a concept car can be slow and costly to construct [5, 34, 44, 45, 57].

In CAVE-based VR [15, 37], screens surrounding a user wearing tracking glasses show perspective-corrected images. However, in this method, only one person can view the VR at a time, limiting its application in the design field, where many designers may need to concurrently collaborate.

In this regard, HMD-based VR [29, 40] holds more promise for a new design workflow, where many designers can wear HMDs as needed and collaborate in the same virtual world [24, 27, 48]. However, authoring experienceable 3D contents directly in VR still remains a challenge.

Rapid Authoring Using 3D Sketching

Sketching is a highly expressive tool for designers, particularly during the early stages of the design process [9], and various 3D sketching techniques aim to transfer the benefits of sketching to the 3D space [17, 42].

In-space 3D sketching utilizes movements of spatially tracked devices [23, 31, 41, 52] or the hand and other body parts [21, 46, 50]. Sketching directly in a 3D space is quick and intuitive, but the result tends to be of lower fidelity due to the lack of haptic feedback [1]. Therefore, this mode of 3D sketching is useful for when the designer wishes to quickly express approximate design intents [55].

Pen- and tablet-based 3D sketching [2, 3, 18, 43, 49, 53], on the other hand, constructs 3D shapes from the user's 2D drawing inputs for relatively higher precision and reduced fatigue. This approach makes the best use of the designer's trained drawing skills but leaves potential benefits offered by VR and other 3D modalities to be desired.

We take a hybrid approach akin to SketchingWithHands [33], where rough 3D references are constructed from the tracked hand information, and more elaborate shapes are sketched upon it using pen and tablet devices.

Immersive VR Using Haptic Helpers

In VR, immersion can be enhanced by the presence of haptic feedback [10, 11, 28], possibly provided by mechanical actuators [4, 13, 51]. However, these devices may not support the natural movements and degree of freedom required for the interaction scenarios of the future automotive interior.

Human haptic helpers can also provide the desired haptic feedback [10, 11]. Although the human-generated haptic effects may not be as precise as those generated by mechanical devices, human helpers have greater mobility and flexibility in enacting haptic feedback, which we believe is more suitable for the purpose of experience prototyping.

Previous works on haptic feedback mainly focused on supplementing existing visual and auditory contents. We, on the other hand, focus on enabling designers to flexibly author haptic effects as an integral part of the interaction concept.

Experience Prototyping Using UI Design Methods

Various experience prototyping methods employed by the UI design community, such as Wizard of Oz [8, 30, 32], bodystorming [8, 30] and quick-and-dirty prototyping [30], can lead to agile automotive UI design. These methods utilize existing materials to quickly create low-fidelity prototypes of interactive systems for rapid and effective expression and evaluation of ideas. The usefulness of these techniques has widely been studied in the fields of human-computer interaction [9, 16, 19, 32, 36] and product design [8, 26, 30]. But, additional consideration is needed to apply these methods to automotive interior interaction design.

ANALYSIS OF EXISTING PROTOTYPING METHODS

In this section, we perform in-depth analysis of existing experience prototyping methods to derive requirements that a workflow specific to designing automotive interior interaction should satisfy.

A1. Make prototypes quickly with minimal fidelity

Designers make prototypes as quickly as they can to experiment with ideas using available materials [26, 30], including paper [9]. To prototype interactive systems, they often use the Wizard of Oz method, in which a hidden person mimics the system by enacting the system's predefined response protocol [9, 26, 36].

A2. Evaluate prototypes in spatial and temporal contexts

Designers move their bodies in spatial contexts to check the physical constraints (bodystorming) [8, 26, 30], develop usage flow scenarios [26, 30] and perform the prescribed actions in temporal sequence.

A3. Simulate users' points of view

Designers use prototypes they designed in realistic contexts and environments [9, 30] to simulate the experience of the user, and they sometimes disguise themselves as users [30] or role-play together [9, 26, 30] to increase immersion.

A4. Observe users with minimal interference

Designers observe users experiencing prototypes without interfering by discreetly following the user (shadowing) [26, 30], standing out of the user's sight (fly on the wall) [26, 30] or recording the user's behaviors with cameras (video ethnography) [26, 35].

A5. Iterate through generation and evaluation
Designers gradually evolve ideas by quickly authoring and evaluating prototypes in an iterative manner [9, 35].

A6. Design with others
Designers collaborate with other designers to share, develop and evaluate ideas from a variety of viewpoints. They also engage technical experts [35], users and other stakeholders through participatory design [26], design workshops [26], usability evaluation [26] and interviews [35].

FORMATIVE STUDY

In order to gauge the effectiveness and limitations of existing experience prototyping methods and identify opportunities for applying 3D sketching and VR in automotive interior interaction design, we conducted a formative study using traditional prototyping methods.

Participants

We conducted 2 workshops with 2 different groups of participants. In Workshop 1, we recruited 18 participants working in automotive parts manufacturing who also drove regularly in order to observe participants generating practical and technologically feasible ideas. In Workshop 2, we recruited 7 college students majoring in industrial design who had no driving experience to observe participants generating more creative and far-fetched ideas.

Procedure

In Workshop 1, we organized 3 teams of 6 people, and in Workshop 2, we organized 2 teams of 3~4 people. Both workshops were conducted using the same procedure.

Idea Generation
We asked participants to generate rough ideas of "what they would need in a car in the year 2025" through brainwriting [25] for 30 minutes in teams. Each team member wrote down ideas on a sheet of paper and handed it over to the next team member in silence to ensure that everyone participated and reflected on others' ideas.

Idea Prototyping
We prepared a prototype environment that substituted desks for front and back walls of a car, curtains for ceilings, acrylic plates for doors and dashboards, and office chairs for car seats. We also provided various craft materials and office supplies for quick-and-dirty prototyping [9, 25, 26, 30, 35]. Participants could freely rearrange or remove any of these interior components.

Based on the results of brainwriting, each team developed future automotive interior ideas for 70 minutes through quick-and-dirty prototyping, bodystorming, and Wizard of Oz methods [9, 25, 26, 30, 35] (Figure 2). Then, after preparing for 30 minutes, each team made a presentation of concepts with an elevator pitch [25] and role-play [30]. After presenting, all concepts were peer-reviewed for 60 minutes, using the new-useful-feasible (NUF) criteria [25].

Figure 2. In a formative study, participants performed (a) quick-and-dirty prototyping with craft materials and office supplies, and (b) bodystorming and Wizard of Oz to simulate future automotive interior interactions.

Findings

We summarize important findings from the formative study that should be incorporated in designing a new experience prototyping workflow.

F1. Hand motion expresses rough ideas in 3D space
During the formative study, we observed that participants used hand gestures to roughly express and communicate complex automotive interior design ideas involving 3D shapes, positions and movements. For example, to describe a steering wheel that automatically retreats in self-driving mode and protrudes in manual driving mode, a participant made grip gestures with two hands in the air, and then thrust the hands forward and backward while verbally explaining the imagined situation.

F2. Expressing detailed 3D shapes is difficult
Participants, however, found it difficult to further develop ideas regarding interior components that had more complex 3D geometry, using only bare hand gestures and available materials. For instance, one participant tried and failed to describe on-demand, pop-up compartments in the trunk that could more efficiently store items of varying sizes and fragility, using only a small cardboard box. Because of this difficulty, many good ideas were not further developed and thus were eventually dismissed.

F3. Presence of others harms immersive experience
In the Wizard of Oz method, the operators simulating the interactive system should be invisible to the user. However, in our study, many operating participants surrounded the experiencing participant to simulate the dynamic and spatial interactions that are expected to fill the future automotive interior. As a result, participants mentioned that immersion was disturbed by the presence of other participants.

F4. Touchability is crucial for evaluating ergonomics
Through quick-and-dirty prototyping and bodystorming, participants could touch and hold physical mockups to evaluate ergonomics, such as reachability of the dashboard and comfort of the armrest. In one case, a participant iterated on an idea of a dynamically adjusted "body-rest" that inflated and deflated around the user to best accommodate the detected body posture, by holding many air cushions against the seated user at various positions.

F5. Collaboration enables simulation of rich interactions
Interactions inside a future car are expected to be visual, aural, tactile, spatial and temporal, further compounding the difficulties of designers to quickly author and reproduce them in any experienceable form. However, we observed that participants could flexibly collaborate to solve this problem; participants organically assumed roles and worked together side-by-side to simulate these rich interactions.

F6. A series of interactions needs to be orchestrated
It takes special effort to simulate a series of interactions as an integrated scenario of the future automotive interior. As the prototyping progressed, we observed one participant orchestrating the interactions, while referring to a scenario script. Other participants followed the lead and performed the prescribed parts accordingly.

DESIGN GOALS & DIRECTIONS

Based on the analysis (A1-A6) of existing experience prototyping methods and the findings (F1-F6) from the formative study, we establish design goals and directions for the new workflow for designers to prototype the interior experience of future cars.

G1. Express roughly using in-space 3D sketching (F1)
Previous works [21, 46, 50] and our formative study show that, while rough, free body movements in space can be utilized as input for quick and intuitive 3D authoring. Thus, we apply an in-space 3D sketching technique with which designers express approximate 3D design intents using bare hand motion in space. Such can be used as a reference for further detailed 3D sketching and constructing physical proxies that supplement the immersive experience.

G2. Express precisely using on-tablet 3D sketching (A5, F2)
To further develop ideas, designers should be able to iteratively and progressively flesh out the rough 3D sketches that they created earlier. However, conventional CAD modeling software used for high fidelity models are not effective for this purpose because model building in these tools requires considerable time and effort, and also because they are suitable for authoring predetermined shapes, not exploring new ones [2, 17, 42]. Thus, we apply an on-tablet 3D sketching technique with which designers quickly draw 3D details on the in-space 3D sketches, using precise pen and tablet devices.

G3. Isolate experience using HMD-based VR (A3, A4, F3)
Strong immersion is critical for experiencing and evaluating interaction ideas. However, when the unmodified Wizard of Oz method is applied to the automotive interior, there would be many operators surrounding the user, enacting many moving parts, thus inevitably distracting the user. Therefore, we utilize HMD-based VR to isolate the user's experience from everything that takes place to prototype that experience. This also enables the observer to closely monitor the user without impeding the experience.

G4. Provide feedback through haptic helpers (A1, A2, F4)
Future automotive interactions are expected to consist of dynamic, visual, aural and haptic input and output, but prototyping these multi-modality inputs and multi-sensory outputs during development in existing automotive design processes can be difficult. Therefore, we introduce haptic helpers to create physical proxies using the quick-and-dirty method and to move and hold them to flexibly simulate haptic and other sensory feedback to the user in VR.

G5. Prototype collaboratively using role playing (A6, F5, F6)
Tight collaboration is important in automotive interaction design, not only for the different perspectives and insights each designer brings, but also for cooperatively enacting complex spatiotemporal multi-sensory interactions. We define interchangeable roles that the designers play and different zones that accommodate different activities to better facilitate such collaboration.

COLLABORATIVE EXPERIENCE PROTOTYPING IN VR

In this section, we explain which roles designers can play, how a workspace is divided and what collaborations take place in *Collaborative Experience Prototyping in VR with 3D Sketching and Haptic Helpers* (CEPVR).

Roles of Designers

In CEPVR, organic collaboration is enabled by designers performing interchangeable roles (Figure 3, 4).

- *Experiencer*: experiences interaction concepts and gives feedback from the first-person perspective in HMD-based VR (Figure 4d, k).
- *In-space sketcher*: roughly sketches virtual models using hand motions tracked by a sensor in HMD-based VR (Figure 4a, k).
- *On-tablet sketcher*: 3D sketches detailed virtual models using digital pen and tablet devices (Figure 4b-c).
- *Proxy maker*: creates physical proxies of virtual models using available materials in HMD-based augmented reality (AR), where the physical task is aided by the overlays of the virtual models (Figure 4e-f).
- *Motion simulator*: controls positions and movements of the virtual models and physical proxies using a VR controller in HMD-based AR (Figure 4j).
- *Effect simulator*: enacts tactile and auditory effects using available gadgets such as a smartphone (Figure 4m).
- *System operator*: administers the virtual environment and virtual models within it (Figure 4n).
- *Experience scribe*: writes and updates an instruction script of the interaction scenario (Figure 4o).
- *Interaction orchestrator*: helps motion simulators, effect simulators and system operators play their parts at the right time by vocally reading the instruction script (Figure 4o).

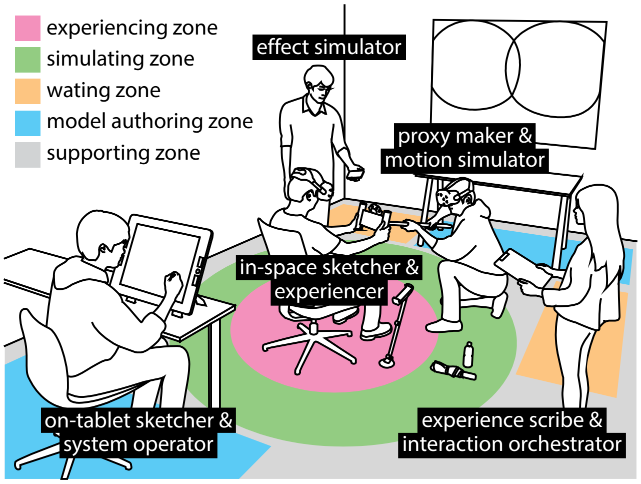


Figure 3. The roles and workspaces can be assigned flexibly, considering the number of participants and available space.

Division of Workspace

For efficient use of space and movement paths of the role players, we divide the workspace in CEPVR (Figure 3).

- *Experiencing zone*: at the center, where the experiencer and the in-space sketcher stay. For optimal immersion, others should try to keep away from this zone.
- *Simulating zone*: surrounding the experience zone, where the motion simulator and the effect simulator temporarily stay. Here, simulators can prepare and perform their roles.
- *Waiting zone*: at the periphery, where simulators wait before entering the simulating zone for their turn.
- *Model authoring zone*: at the periphery, where the on-tablet sketcher and proxy maker stay. Located here are the pen and tablet devices, as well as various other props.
- *Supporting zone*: remaining spaces, where the system operator, scenario scribe and interaction orchestrator stay. Located here are a desktop computer running the system and a screen displaying the viewpoint of the experiencer.

Collaboration

Each designer plays one or more interchangeable roles collaboratively. One such instance is shown in Figure 4.

Collaboration for initial ideation

Designers collaboratively author rough 3D shapes that serve as building blocks for further development (Figure 4a-d).

First, the designer who is both the *experiencer* and *in-space sketcher* enters HMD-based VR and creates rough 3D shapes using hand motion, while considering factors such as space constraints and ergonomics (Figure 4a). The designer experiences the user's perspective, and thus is in the best position to make these initial design decisions. The tracked hand motion immediately appears on the tablet device of the on-tablet sketcher as crude 3D wireframe surfaces (Figure 4b), conveying approximate design intents such as 3D position, proportion and scale.

Next, the *on-tablet sketcher* draws 3D sketches on top of the 3D wireframe surfaces (Figure 4c), using pen drawing skills to sketch 3D details that the *in-space sketcher* would find difficult to describe with hand motions alone. The 3D sketches immediately appear in the VR (Figure 4d). Here, the 3D sketches are anchored to the 3D contexts determined by the first designer, who can then comment on the 3D sketch or even make more 3D wireframe surfaces at any time, for fluid and iterative development.

Collaboration for design development

The collaboratively created virtual 3D sketches then trigger construction of physical proxies and development of more fully-fledged interactions (Figure 4e-n).

First, wearing HMD-based AR to check the dimensions of the 3D sketch models (Figure 4e), the *proxy maker* quickly makes the corresponding low-fidelity physical proxies, using available raw materials and props (Figure 4f). With the *motion simulator* holding the created proxies in place (Figure 4g), the *experiencer* can then not only see the 3D sketches but also reach out and touch them (Figure 4h). Based on the *experiencer*'s feedback on matters such as ergonomics and texture, the *on-tablet sketcher* and *proxy maker* can iteratively update the virtual model and the proxy, respectively (Figure 4i).

Then, the *motion simulator* designs interaction movements. In order to synchronize the motion with visual and haptic feedback, the motion simulator moves a VR controller and the physical proxy simultaneously. The motion is visualized as a separate 3D curve (Figure 4j). As such, the designer who is both the *experiencer* and *in-space sketcher* can visually and physically sense the motion inside the car and provide feedback on the motion verbally or through the hand motion in-space sketches (Figure 4k). The *motion simulator* views this feedback through the HMD-based AR and updates the motion to reflect it (Figure 4l).

To simulate multi-sensory interaction, the *effect simulator* and *system operator* collaborate to augment sound, light and vibration effects. They closely communicate with the *experiencer* to determine details such as suitable trigger, position, timing and play pattern of these effects. The *effect simulator* uses the ringtones and vibration of a smartphone for audio-tactile effects, and voice for speech interface (Figure 4m). The *system operator*, meanwhile, manipulates the VR software to generate visual effects (Figure 4n).

Collaboration for integrated experience

Because the designers can immediately experience visual, aural and haptic aspects of spatiotemporal interaction ideas through enactment, they can quickly explore a wide array of different ideas, immersively evaluate the desirability of each, and iteratively and progressively build toward a unified automotive interior interaction scenario.

At this stage, the *experience scribe* observes the prototyped experience and formulates an instruction script, which the *interaction orchestrator* uses to coordinate the *motion simulator* and *effect simulator* (Figure 4o). The simulators closely listen to these instructions, enter the simulating zone when their roles become imminent and then perform the roles on time. The *experiencer*’s view of the VR is broadcast on a screen that everyone can always refer to as they coordinate and perform their enactments.

IMPLEMENTATION

We implemented our workflow in a room-sized space with off-the-shelf equipment to simulate an actual design studio.

VR studio environment

We set up our prototype environment in a 3 m × 4 m room in which a virtual car model and up to 10 people could fit. VR was implemented using HTC Vive VR headsets and controllers, a desktop PC with an Intel i7 3.6 GHz CPU and an Nvidia GeForce GTX 1080 GPU, a Unity game engine, Leap Motion SDK and a SteamVR plugin. An LG PF1000U short-throw projector displayed the experiencer’s viewpoint on a 1.7 m × 2 m projection screen for others to see.

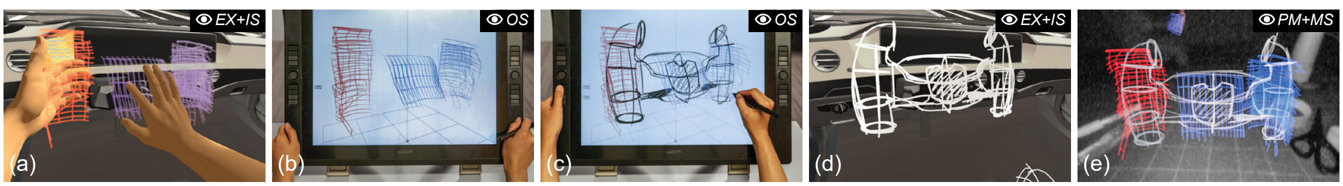
In-space and on-tablet 3D sketching system

For in-space sketching, a Leap Motion sensor attached to HMD captured hand motions, and for on-tablet sketching, a Wacom Cintiq 21UX tablet captured pen drawing inputs. The sketching system based on SketchingWithHands [33] written in Java and OpenGL ran on a PC with an Intel i7 2.7 GHz CPU and an Nvidia Quadro K2000M GPU.

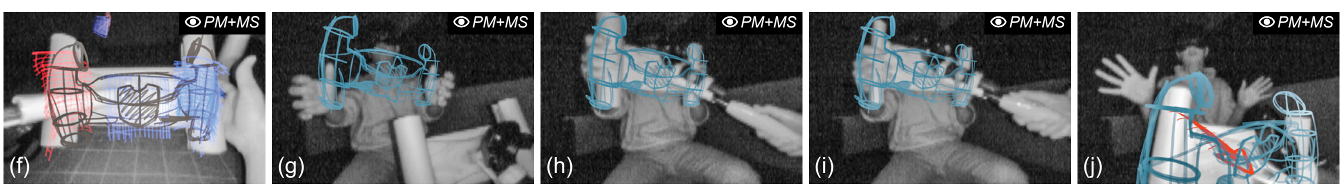
Physical tools and materials used for prototyping

To quickly make physical proxies as needed, it is important to prepare an abundance of tools and materials in advance. The following are examples of the tools and materials used:

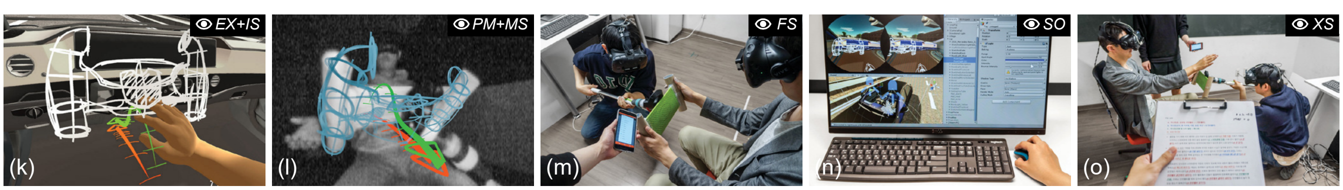
Rigid and flexible plate-like props for surfaces; cylindrical props for grips; metallic wire for organic shapes; empty boxes for volumes; different types of fabric for various textures; and office supplies for combining several props. In addition, a long rod with a physical proxy attached at the end was used to provide haptic feedback to the *experiencer* from a distance. For sound and vibration, the *effect simulator* used an LG Nexus 5X Android smartphone and its built-in ringtones and vibration patterns, or even the YouTube app to find and play an appropriate sound.



(a) *EX+IS* expresses the shape of the steering wheel by moving hands in the virtual space.
(b) It is visualized on *OS*’s pen tablet display as 3D wireframe surfaces.
(c) Based on the wireframes, *OS* sketches the details of the steering wheel on the tablet.
(d) The on-tablet sketched steering wheel becomes immediately visible to *EX+IS*.
(e) Also, the steering wheel sketches are displayed in the AR workspace of *PM+MS*.



(f) *PM+MS* makes a physical proxy by using props such as toilet paper tubes and a mop stick.
(g) *PM+MS* moves the physical proxy to the experiencing zone.
(h) After holding the steering wheel, *EX+IS* requests to reduce the radius of the grips.
(i) Reflecting the feedback, *PM+MS* quickly makes the proxy’s grips thinner and *EX+IS* re-experience it.
(j) To enact the motion, *PM+MS* moves both the proxy and the virtual model, leaving the motion path (red).



(k) *EX+IS* expresses modifications (green) by moving the hand over the existing motion path.
(l) *PM+MS* enacts the movement of the steering wheel along the modified motion path in AR.
(m) To simulate the vibration notification, *FS* holds a vibrating smartphone against the physical proxy.
(n) To simulate the LED notification, *SO* uses VR software to change the lighting parameters of the virtual environment.
(o) *XS* writes a script and *IO* reads it aloud to help *PM+MS, FS,* and *SO* to enact the integrated scenario when switching to autonomous mode.

Figure 4. In CEPVR, designers prototype the steering wheel interaction when switching to autonomous driving mode. Eye symbols (upper right) indicate the perspective of the role player (EX: experiencer, IS: in-space sketcher, OS: on-tablet sketcher, PM: proxy maker, MS: motion simulator, FS: effect simulator, SO: system operator, XS: experience scribe, IO: interaction orchestrator).

USER TEST

We conducted a user test with our implemented system to observe how our intended users utilize CEPVR and to obtain their qualitative feedback.

Participants

Nine participants of varying ranks (6 senior (S); 3 junior (J)) and positions (6 researchers (R); 2 designers (D); 1 product manager (M)) were recruited from an automotive interior parts company. Because design projects tend to involve members with different responsibilities and backgrounds, we divided our participants into 2 groups. Group A (SR1, SR2, JR1, JM1) was responsible for interaction design and Group B (SR3, SR4, SR5, SD1, JD1) for evaluation.

Procedure

We documented our observations and video-recorded the entire process during the user test.

Initial design session

Based on the given contextual scenario (business travel in a shared autonomous car), Group A members collaboratively prototyped an experience for 2 hours. They iteratively and progressively decided on design details such as component positions, movement speed and paths, and intensity of vibration effects, toward an integrated interaction scenario.

Design evaluation session

Group B members then joined the design process and experienced the interaction scenario that Group A designed and enacted by taking turns entering the HMD-based VR, then provided feedback. All the other non-experiencing participants could observe both the virtual scene projected on the screen and the physical scene.

Survey and group interview session

After the evaluation session, we administered a post hoc questionnaire on the pros and cons, suggestions for CEPVR and thoughts on future automotive interior interactions having experienced them firsthand. Then, we gathered the 9 participants and held an in-depth group discussion.

USER FEEDBACK AND DISCUSSION

In order to examine how CEPVR had helped participants in designing future automotive interior interactions (Figure 5), we analyzed our observation from the user test and the group interview and clustered topics by similarity [26, 30].

Multi-sensory experience led to in-depth understanding

Through multi-sensory experience involving visual, aural and haptic stimuli, the participants could better grasp the interaction concepts that had complex spatial and temporal dimensions (Figure 5b, c). They intuitively understood the ergonomic and emotional qualities better than they could with any written or illustrated descriptions. JM1 said, “*Differences between ideas became clearer*”; SR5 said, “*Experiencing interactions with my body elicited emotions that led to more vivid understandings*”; and SR3 said, “*Experience was better than a thousand words or pictures*.”

Immersive experience led to more constructive feedback

The participants could immerse themselves in the user’s perspective in interaction scenarios to evaluate concepts and provide more constructive feedback. SR5 said, “*Disruptions that car-sharing services will bring in the near future could be easily seen*” and suggested a novel idea of automatic vending machines inside the shared cars. While evaluating the idea of using the passenger seat window as a cosmetic mirror for drivers, JR1 said, “*It is too far away to see my face on it,*” a feedback that would not have been possible if JR1 did not observe the distance from the user’s perspective.

3D sketching was suitable for rapid experience prototyping

During the group interview, participants noted that the 3D curve sketches were not photorealistic, but that these were sufficient for them to understand the shape and immersively experience the concept in an immersive way (Figure 5b). JD1 said “the, “The sketch models lacked the sense of reality, but there was no problem being immersed.” We found that 3D sketching is effective in the early design stage, where quick exploration and experiencing take precedence over high fidelity.

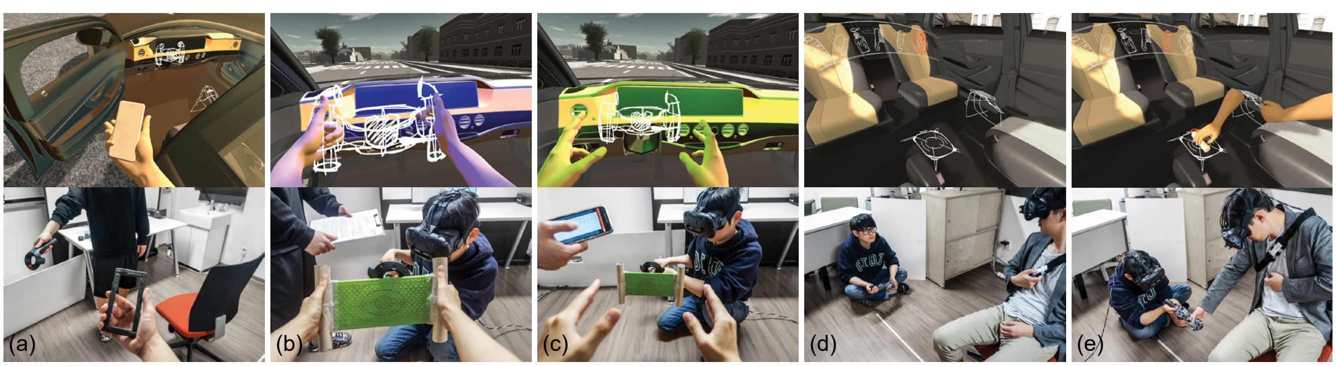


Figure 5. Reproduction of the integrated interaction scenario designed during the user test. (a) Authentication via the smartphone and the automatic door. (b) LED and AI voice guidance during driving mode transition. (c) LED and sound notifications and the steering wheel’s retrieval during autonomous driving. (d) Interface for selecting and retrieving luggage from the trunk using touch input on the seat belt. (e) Receiving an umbrella before leaving the car. (Note: (a), (b), (c) are the views from the driver experiencer and (d), (e) are the views from the passenger experiencer. In each, upper and lower are the VR and physical views of the same scene.)

Low-fidelity proxies sufficiently enhanced immersion

Even low-fidelity physical proxies could provide haptic feedback sufficient for enhancing immersion (Figure 5a, b, e). Some participants, when they reached out their hands to a 3D sketch, were pleasantly surprised that they could actually touch it, and even gave exclamations. During the group interview, JR1 said, "*Experience was amplified by the sense of touch,*" demonstrating that when the vision is virtually stimulated by an HMD, even approximate haptic feedback can be effective [11, 12].

Proficiency allowed more sophisticated simulations

At the beginning, the Group A members could only enact the simplest interactions. However, as they spent more time, the group's proficiency to collaboratively enact interactions became considerably higher, leading to more detailed and refined interaction simulations, better immersion and more sophisticated feedback. The group's final scenario was more than 10 minutes of sequential interactions, but the group, by then, was undaunted and could confidently enact the sequence precisely and efficiently.

CEPVR is applicable to other fields and practices

Many participants thought that CEPVR is applicable to their respective fields, in addition to the future car interior. SD1, a design team leader, said, "*The workflow would be useful in exploring new materials for car seats.*" SR4, from an advanced research team, said, "*The workflow could be used to quickly discern worthy ideas that the company should invest in.*" Also, SR1, an R&D team leader, said, "*It would be a great tool for facilitating communication with other members of the company who have never participated in a design process, and bringing them onboard.*"

LIMITATIONS AND FUTURE WORK

Although the participants gradually became more proficient at enactment, spatiotemporal interaction sequences can be so complex that unaided human helpers cannot enact them with sufficient fidelity to evoke an immersive experience, such as interactive components moving along delicate 3D paths in a concerted manner. Studies on human actuation suggest that temporal cues [10] and 2D spatial cues [11] can significantly enhance such performances. Thus, future work should focus on aiding the helpers. For instance, an augmented 3D motion path with marks that need to be crossed at certain times can aid helpers to enact motion at the right pace.

Some promising early ideas designers had were lost during the process because there was no suitable means to record and manage the sporadically generated interaction ideas. Written and illustrated descriptions cannot convey rich spatiotemporal interactions involving visual, aural and haptic stimuli, and raw video recordings of long design sessions can be difficult to search through. Thus, future work should focus on helping designers easily manage each unit of 3D interaction to effectively store and recall it.

While qualitative feedback from the user test confirms the usefulness of CEPVR in future automotive interior interaction design, more work is needed on additional evaluation, such as an in-field, long-term user study in comparison with alternative methods and application to broader human-machine interface (HMI) domains.

CONCLUSION

Attempts to innovate the automotive design process through introduction of advanced computer graphics and interactive technologies are ongoing. In this line of work, we proposed CEPVR, a new workflow that invokes the latest VR and 3D content creation methods as well as experience prototyping methods typically embraced by the UI design community, with a focus on rich, spatiotemporal interaction between the passengers and the interior space of the future car.

We empirically confirmed the usefulness of CEPVR, showing that 3D sketching and experience prototyping afford quick, flexible, iterative and progressive ideation, prototyping, experiencing and evaluation in collaboration. We believe that our workflow can significantly increase the breadth and depth of concept exploration of possible rich interactions in the early design stage, ultimately leading to better human-vehicle interaction inside the future car.

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REFERENCES

1. Rahul Arora, Rubaiat Habib Kazi, Fraser Anderson, Tovi Grossman, Karan Singh, and George Fitzmaurice. 2017. Experimental evaluation of sketching on surfaces in VR. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (CHI '17), 5643-5654.
2. Seok-Hyung Bae, Ravin Balakrishnan, and Karan Singh. 2008. ILoveSketch: as-natural-as-possible sketching system for creating 3d curve models. In *Proceedings of the 21st annual ACM symposium on User interface software and technology* (UIST '08), 151-160.
3. Seok-Hyung Bae, Ravin Balakrishnan, and Karan Singh. 2009. EverybodyLovesSketch: 3D sketching for a broader audience. In *Proceedings of the 22nd annual ACM symposium on User interface software and technology* (UIST '09), 59-68.
4. Hrvoje Benko, Christian Holz, Mike Sinclair, and Eyal Ofek. 2016. NormalTouch and TextureTouch: high-fidelity 3D haptic shape rendering on handheld virtual reality controllers. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology* (UIST '16), 717-728.

5. BMW Press Release. 2016. BMW opts to incorporate HTC Vive VR headsets and mixed reality into the development of new vehicle models. Retrieved April 27, 2017 from https://www.press.bmwgroup.com/global/article/detail/T0258902EN/bmw-opts-to-incorporate-htc-vive-vr-headsets-and-mixed-reality-into-the-development-of-new-vehicle-models-computer-images-instead-of-laboriously-constructed-draft-models:-greater-flexibility-faster-results-and-lower-costs
6. Frederik P. Brooks.1999. What's real about virtual reality?. *IEEE Computer graphics and applications* 19, 6, 16-27.
7. Chris Bryant. 2014. Heads up on latest in augmented reality displays for cars. Retrieved July 21, 2017 from https://www.ft.com/content/e32fcc04-643b-11e4-bac8-00144feabdc0?mhq5j=e2
8. Marion Buchenau and Jane Fulton Suri. 2000. Experience prototyping. In *Proceedings of the 3rd conference on Designing interactive systems: processes, practices, methods, and techniques* (DIS '00), 424-433.
9. Bill Buxton. 2010. *Sketching user experiences: getting the design right and the right design.* Morgan Kaufmann.
10. Lung-Pan Cheng, Patrick Lühne, Pedro Lopes, Christoph Sterz, and Patrick Baudisch. 2014. Haptic turk: a motion platform based on people. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '14), 3463-3472.
11. Lung-Pan Cheng, Thijs Roumen, Hannes Rantzsch, Sven Köhler, Patrick Schmidt, Robert Kovacs, Johannes Jasper, Jonas Kemper, and Patrick Baudisch. 2015. TurkDeck: physical virtual reality based on people. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology* (UIST '15), 417-426.
12. Lung-Pan Cheng, Eyal Ofek, Christian Holz, Hrvoje Benko, and Andrew D. Wilson. 2017. Sparse haptic proxy: touch feedback in virtual environments using a general passive prop. *In Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (CHI '17), 3718-3728.
13. Inrak Choi and Sean Follmer. 2016. Wolverine: a wearable haptic interface for grasping in VR. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology* (UIST '16 Adjunct). ACM, New York, NY, USA, 117-119.
14. Jamie Condliffe. 2017. Holograms and Alexa are coming to a car near you. Retrieved July 21, 2017 from https://www.technologyreview.com/s/603307/holograms-and-alexa-are-coming-to-a-car-near-you/
15. Carolina Cruz-Neira, Daniel J. Sandin, and Thomas A. DeFanti. 1993. Surround-screen projection-based virtual reality: the design and implementation of the CAVE. In *Proceedings of the 20th annual conference on Computer graphics and interactive techniques* (SIGGRAPH '93), 135-142.
16. Richard C. Davis, T. Scott Saponas, Michael Shilman, and James A. Landay. 2007. SketchWizard: Wizard of Oz prototyping of pen-based user interfaces. In *Proceedings of the 20th annual ACM symposium on User interface software and technology* (UIST '07), 119-128.
17. Chao Ding and Ligang Liu. 2016. A survey of sketch based modeling systems. *Frontiers of Computer Science* 10, 2: 985-999.
18. Julie Dorsey, Songhua Xu, Gabe Smedresman, Holly Rushmeier, and Leonard McMillan. 2007. The mental canvas: a tool for conceptual architectural design and analysis. In *15th Pacific Conference on Computer Graphics and Applications* (PG '07), 201-210.
19. Steven P. Dow, Manish Mehta, Blair MacIntyre, and Michael Mateas. 2010. Eliza meets the wizard-of-oz: blending machine and human control of embodied characters. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '10), 547-556.
20. Michele Fiorentino, Raffaele de Amicis, Giuseppe Monno, and Andre Stork. 2002. Spacedesign: a mixed reality workspace for aesthetic industrial design. In *Proceedings of the 1st International Symposium on Mixed and Augmented Reality* (ISMAR '02), 86-94.
21. Mark Fuge, Mehmet Ersin Yumer, Gunay Orbay, and Levent Burak Kara. 2012. Conceptual design and modification of freeform surfaces using dual shape representations in augmented reality environments. *Computer-Aided Design* 44, 10 (Oct.), 1020-1032.
22. David K Gibson. 2016. Why car designers stick with clay. Retrieved July 21, 2017 from http://www.bbc.com/autos/story/20161111-why-car-designers-stick-with-clay
23. Google Tilt Brush. 2016. https://www.tiltbrush.com
24. Gravity Sketch. 2014. https://www.gravitysketch.com
25. Dave Gray, Sunni Brown, and James Macanufo. 2010. *Gamestorming: A playbook for innovators, rulebreakers, and changemakers*. O'Reilly Media, Inc.
26. Bruce Hanington and Bella Martin. 2012. *Universal methods of design: 100 ways to research complex problems, develop innovative ideas, and design effective solutions.* Rockport Publishers.
27. Rorik Henrikson, Bruno Araujo, Fanny Chevalier, Karan Singh, and Ravin Balakrishnan. 2016. Multi-device storyboards for cinematic narratives in VR. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology* (UIST '16), 787-796.
28. Hunter G. Hoffman. 1998. Physically touching virtual objects using tactile augmentation enhances the realism of virtual environments. In *Proceedings of Virtual Reality Annual International Symposium* (VRAIS '98), 59-63.

29. HTC Vive. 2016. https://www.vive.com
30. IDEO. 2003. *IDEO Method Cards: 51 Ways to Inspire Design*. William Stout Architectural Books.
31. Daniel F. Keefe, Robert C. Zeleznik, and David H. Laidlaw. 2007. Drawing on air: input techniques for controlled 3D line illustration. *IEEE Transactions on Visualization and Computer Graphics* 13, 5 (Mar.), 1067-1081.
32. John F. Kelley. 1984. An iterative design methodology for user-friendly natural language office information applications. *ACM Trans. Inf. Syst.* 2, 1 (January 1984), 26-41.
33. Yongkwan Kim and Seok-Hyung Bae. 2016. SketchingWithHands: 3D sketching handheld products with first-person hand posture. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology* (UIST '16), 797-808.
34. Leo King. 2014. Ford, where virtual reality is already manufacturing reality. Retrieved April 27, 2017 from https://www.forbes.com/sites/leoking/2014/05/03/ford-where-virtual-reality-is-already-manufacturing-reality/#1ea4af186e4d
35. Vijay Kumar. 2012. *101 design methods: A structured approach for driving innovation in your organization.* John Wiley & Sons.
36. Sang-Su Lee, Jeonghun Chae, Hyunjeong Kim, Youn-kyung Lim, and Kun-pyo Lee. 2013. Towards more natural digital content manipulation via user freehand gestural interaction in a living room. In *Proceedings of the 2013 ACM international joint conference on Pervasive and ubiquitous computing* (UbiComp '13). 617-626.
37. Valerie D. Lehner and Thomas A. DeFanti. 1997. Distributed virtual reality: supporting remote collaboration in vehicle design. *IEEE Computer Graphics and Applications* 17, 2, 13-17.
38. Roger Martin. 2009. *The design of business.* Harvard Business Review Press.
39. Christian Muller and Garrett Weinberg. 2011. Multimodal input in the car, today and tomorrow. *IEEE MultiMedia* 18, 1, 98-103.
40. Oculus Rift. 2016. https://www.oculus.com
41. Oculus Quill. 2016. https://www.oculus.com/story-studio/quill
42. Luke Olsen, Faramarz F. Samavati, Mario Costa Sousa, and Joaquim A. Jorge. 2009. Sketch-based modeling: a survey. *Computers & Graphics* 33, 1 (Feb.), 85-103.
43. Amit Pitaru. 2003. Rhonda. http://rhondaforever.com
44. Frank Purschke, Malte Schulze, and Peter Zimmermann. 1998. Virtual reality-new methods for improving and accelerating the development process in vehicle styling and design. In *Computer Graphics International, 1998. Proceedings*, 789-797.
45. Holger Regenbrecht, Gregory Baratoff, and Wilhelm Wilke. 2005. Augmented reality projects in the automotive and aerospace industries. *IEEE Computer Graphics and Applications* 25, 6, 48-56.
46. Steven Schkolne, Michael Pruett, and Peter Schröder. 2001. Surface drawing: creating organic 3D shapes with the hand and tangible tools. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '01), 261-268.
47. David Talbot. 2012. AT&T Reinvents the Steering Wheel. Retrieved July 21, 2017 from https://www.technologyreview.com/s/427299/att-reinvents-the-steering-wheel/
48. Teague. 2017. Prototyping Car UX in VR. Retrieved July 21, 2017 from http://labs.teague.com/?p=2299
49. uMake. 2016. https://www.umake.xyz
50. Edit Varga, Imre Horváth, Zoltán Rusák, Bram de Smit, and Han Broek. 2004. Survey and investigation of hand motion processing technologies for compliance with shape conceptualization. In *ASME 2004 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 575-587.
51. Emanuel Vonach, Clemens Gatterer, and Hannes Kaufmann. 2017. VRRobot: robot actuated props in an infinite virtual environment. In *Proceedings of IEEE Virtual Reality 2017*, 74-83.
52. Gerold Wesche and Hans-Peter Seidel. 2001. FreeDrawer: a free-form sketching system on the responsive workbench. In *Proceedings of the ACM symposium on Virtual reality software and technology* (VRST '01), 167-174.
53. Min Xin, Ehud Sharlin, and Mario Costa Sousa. 2008. Napkin sketch: handheld mixed reality 3D sketching. In *Proceedings of the 2008 ACM symposium on Virtual reality software and technology* (VRST '08), 223-226.
54. Yasusato Yamada. 1997. *Clay Modeling: Techniques for Giving Three-dimensional Form to Idea.* San'ei Shobo Publishing Co.
55. Yupeng Zhang, Teng Han, Zhimin Ren, Nobuyuki Umetani, Xin Tong, Yang Liu, Takaaki Shiratori, and Xiang Cao. 2013. BodyAvatar: creating freeform 3D avatars using first-person body gestures. In *Proceedings of the 26th annual ACM symposium on User interface software and technology* (UIST '13), 387-396.
56. Chris Ziegler. 2015. BMW's AirTouch concept turns your entire car into a touchscreen controller. Retrieved July 21, 2017 from https://www.theverge.com/2015/12/28/10674062/bmw-airtouch-i8-spyder-ces-2016.
57. Peter Zimmermann. 2008. Virtual reality aided design. A survey of the use of VR in automotive industry. *Product Engineering*, 277-296.