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How does it feel to fly in an air taxi? Exploring modern head-mounted display capabilities for mixed reality flight simulation

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Abstract

The acceptance of air taxi passengers is expected to be a relevant factor for the success of urban air mobility. The authors follow a user-centered design approach—which involves potential users as early as possible—to reach this goal. However, this requires a highly customizable simulation environment where different cabin arrangements and interface designs can be realized and evaluated quickly and cost-efficiently. At the same time, the experience must be immersive enough to give the users the feeling of a realistic flight. This article analyzes available mixed reality technologies and explains how these can be applied to create a simulator that fulfills these requirements. The focus is on head-mounted displays with video-see-through functionality, which allows the fusion of a customizable computer-generated world with a video stream of the real surroundings. The work includes the development of different approaches for the blending of real and virtual content as well as for the user interaction with mixed reality. The four resulting setups are then assessed in an experiment with twelve participants. Thereafter, the favored setup was improved and used for a human-in-the-loop study with 30 participants investigating passenger acceptance aspects of air taxi operations. Both studies confirm the usefulness of the mixed reality approach for the development of a future urban air mobility system. Regarding the various setups, users rated the completely virtual variant as the most immersive but favored the interaction with a physical input device over a virtual touch display. Further, the experiment emphasized the importance of precise alignment between real and virtual contents, which must be ensured by high-quality tracking systems and correct calibration of the video-see-through goggles.

Keywords Head-mounted display · Mixed reality · Video-see-through HMD · Flight simulator · Augmented reality · Virtual reality · Urban air mobility

Abbreviations

AR	Augmented reality
AV	Augmented virtuality
DLR	German Aerospace Center
EASA	European Aviation Safety Agency
HMD	Head-mounted display
LCD	Liquid crystal display
MC_{RI}	Mixed Cabin – Real Interaction
MC_{VI}	Mixed Cabin – Virtual Interaction
MR	Mixed reality
NASA	National Aeronautics and Space Administration
PPD	Pixels per degree
RC	Real Cabin
UAM	Urban air mobility
UAV	Unmanned aerial vehicle
UI	User interface
VC	Virtual Cabin
VR	Virtual reality
VST	Video-see-through
XR	Generic term (AR, VR, MR)
XR-Sim	XR simulator

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1 Introduction

In recent years we have seen large efforts from research, industry, and regulatory institutions to make the long-cherished dream of the flying cab come true [1–3]. Concepts to integrate aerial public transport into urban environments are called "urban air mobility" or more general "advanced air mobility" [4]. The implementation of such a new transport system involves many fields, from the ground infrastructure via the vehicle to a functional and safe traffic management

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system. Numerous aspects of urban air mobility (UAM) were examined in "HorizonUAM" [5] — a research project conducted by several institutes of the German Aerospace Center (DLR). The work described here was performed as part of this project.

Public acceptance and user adoption are expected to be one of the relevant factors for the successful implementation of UAM [3, 6]. A broad study on social acceptance aspects of UAM operations is provided by the European Aviation Safety Agency (EASA) [7]. Further, Straubinger et al. [3] summarize acceptance drivers for potential future passengers that were found by previous research. These include, for instance, perceived reliability, safety, and the user's affinity towards automation. The "Technology Acceptance Model for Disruptive Transport Technologies" presented by Al Haddad et al. [8] describes how several factors (e.g., perceived vehicle safety or previous automation experience) build trust in the system, which increases perceived usefulness and in the end leads to UAM adoption.

The authors' approach is to address these important user-related factors as early as possible in the design and development process of air taxis and UAM systems in general (e.g., [9, 10]). A major challenge in this user-centered design procedure is that most people neither have a clear understanding of the service nor had access to the technology as air taxis are not in operation yet. Thus, the authors plan to use human-in-the-loop simulations to give potential users the chance to experience a simulated flight in an air taxi cabin simulator and thereby develop and formulate their perspective and needs with regard to the future system. In that process, the researchers can explore the influence of the different cabin designs, flight maneuvers, onboard procedures, or abnormal situations — at an early design stage before the first real air taxi is actually built.

To conduct this kind of research the authors require a simulation environment that is highly customizable while providing the required degree of fidelity and being affordable. For rapid prototyping of new cabin or user interface designs, the mockup must be adaptable enough to quickly change the appearance and arrangement of its elements. At the same time, however, the perceived realism must be high enough to immerse the study participants into the simulated situation to enable the researchers to gain valid user acceptance measurements. The interdependence between the three factors (flexibility, level of fidelity, and costs) is nicely described by the simulator continuum proposed by Oberhauser et al. [11]. It states that high fidelity is usually paid by low flexibility and high costs. Conventional full-flight simulators integrating numerous different hard- and software modules and large and expensive high-definition outside vision projection systems range at this end of the continuum. They usually replicate one specific aircraft model (e.g., Airbus A320); the user interface and the cockpit structure cannot be changed easily. Thus, such simulators are not well suited to this type of research. According to Oberhauser's continuum a reasonable trade-off between flexibility, level of fidelity, and costs is offered by mixed reality flight simulators, where the users wear a head-mounted display that immerses them into a (partly) computer-generated world.

Such simulators can bridge the gap between desktop and full-flight simulation for human factors and cockpit design research [12]. Furthermore, the helicopter manufacturer Bell reports that they drastically reduced the cost and time required to design their futuristic concept aircraft FCX-001 by using virtual reality goggles [13]. Similarly, mixed reality simulators seem to be an interesting choice for pilot training (cockpit familiarization [14], procedure training [15], or even qualified flight training [16, 17]). Gomes Araujo et al. [18] describe how various types of mixed reality (MR) systems can be used for different phases and areas of UAM — from simulation in the development stage to operator assistance in the final, productive system. An overview of previous work in this context is provided by Santhosh et al. [19].

This article describes the development and first evaluations of a mixed reality air taxi simulator at DLR's Institute of Flight Guidance. The first section offers an introduction to mixed reality and the various types of head-mounted displays. Section 2 explains the implemented system including detailed comparisons of different methods for the blending of real and virtual content as well as different approaches to realize the user interaction with the mixed reality setup. Section 3 describes a human-in-the-loop study that was conducted to evaluate the simulator and to compare the advantages and limitations of the implemented setup variants. Section 4 presents a consecutive study in which the developed simulator was used to assess several passenger acceptance aspects of future air taxi flights. The final Sect. 5 discusses the findings and draws conclusions on how the MR simulator can be useful for future research on UAM acceptance. Parts of this article have been published in two previous conference publications and a dissertation ([20, 21]: Sect. 1.1, 1.2 and 2 partly; [22]: Sect. 3, Figs. 7, 8, 9, 10, 11, 12 are reprinted with permission from IEEE (©2022 IEEE).

1.1 What is mixed reality?

Augmented, virtual, and mixed reality are a hot topic in today's consumer electronics as well as in professional applications. Unfortunately, the terms are often used inconsistently or even interchangeably, although they do not describe the same thing. A widely accepted taxonomy to structure the various "realities" is provided by Milgram and Kishino [23]. As sketched in Fig. 1, they define a "reality-virtuality continuum" ranging from an entirely real environment on the left to a fully virtual, computer-generated world at the right

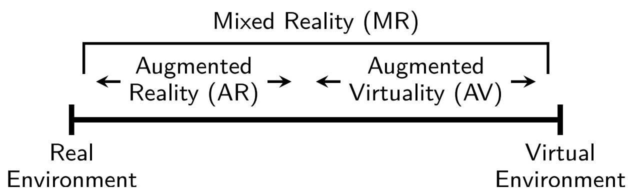


Fig. 1 Reality-virtuality continuum by Milgram and Kishino (adapted from [23])

pole. The latter is often referred to as virtual reality (VR). The whole range between these two poles is called MR. It is a "continuous spectrum of possible combinations of real and virtual content" [24]. Depending on the rate of mixture between real and virtual elements, MR can be divided into its subgroups augmented reality (AR) and augmented virtuality (AV). AR is then defined as any experience where the real environment is enhanced by virtual content. Analogously, AV refers to computer-generated environments augmented with real-world content.

Azuma [25] further specifies AR as a system with the following characteristics: "1. Combines real and virtual, 2. Is interactive in real time, 3. Is registered in three dimensions." He states that ideally both real and virtual objects perfectly coexist in the same 3-D space. This well-known definition narrows down Milgram's notion as it additionally requires 3-D registration and real-time interaction. As a consequence, simple 2-D overlays often presented by data glasses are not AR according to this definition. Further, Azuma explicitly includes all human senses (not only the visual channel) and explains that AR could also *remove* real elements even though the current focus often is on *adding* virtual content.

Additionally, the abbreviation XR is often used — however, with more than one meaning. It can describe extended reality, mixed reality (similar to MR), cross reality, or serve as a generic term with 'X' being a placeholder for M(R), A(R), or V(R) [26–28]. In this paper, we use it in the latter meaning.

1.2 Different types of head-mounted displays to create a mixed reality

A very common way to create the visual[1] part of mixed or virtual realities are HMDs. Figure 2 compares the different types of HMDs that are available to realize experiences in each area of the reality-virtuality continuum. All variants have in common that they feature an image source (e.g., a liquid crystal display)) and an optical system (lenses, waveguides, etc.), which delivers a computer-generated virtual image to the user's eyes (red arrows in Fig. 2). Depending on the type of device, this virtual information may somehow be mixed with a view of the real world (blue arrows).

Optical see-through HMDs — often referred to as augmented reality glasses — contain a beam splitter or "combiner", an optical element that reflects the virtual image from the display into the user's eyes and simultaneously lets the real-world photons pass through [29]. Hence, the user sees the virtual symbology superimposed onto their natural sight. The advantage of these transparent HMDs is that the real-world view is directly[2] seen, which keeps the natural feeling of presence in the real world [30]. However, a major limitation of these devices is that they can only *add* symbology on top of the real scene. This means that virtual elements cannot occlude real objects behind them and colors may appear shifted due to the blending [31]. Further, one can only add light to reality without the ability to selectively dim the surroundings to allow control of contrast. Therefore, there is no ability to use (dark) colors — only colors brighter than the surrounding natural vision. Currently, the probably best-known enterprise optical see-through HMD is the Microsoft HoloLens 2 [32] depicted in Fig. 2. Further, this technology has been developed and used in military aviation for several decades [33–35]

Non-see-through HMDs — often called VR goggles — show a virtual scene via a rather simple optical system: Mostly it is simply a collimating lens in front of the image source. They are typically designed as immersive devices, which means that a ski-goggle-like housing entirely blocks the view of the real environment. Even though the *view* is virtual only, one can still create a *mixed* reality as this term covers more than just the visual sense. Real-world objects can, for instance, be added to create haptic feedback. In the case of an MR flight simulator, this can be physical flight control devices, cockpit instruments, buttons et cetera (e.g., [11, 36]). In contrast to the see-through devices described above, VR-HMDs offer saturated colors and high contrast because the virtual image does not "compete" with the outside world [30]. Over the last few years, many VR glasses that work according to this principle have come onto the market. Examples include the Oculus Rift CV 1 seen in Fig. 2, the Varjo Aero [37], and the Pimax 8K X [38]. Please note, however, that most recent consumer headsets offer a so-called pass-through feature which makes them belong to the "video-see-through" category described below.

Video-See-Through HMDs feature two cameras integrated into the front of their housing. These provide a stereo video stream of the surrounding reality, which is then shown on the display. A "mixed reality" can be created by blending the streamed imagery with virtual symbology.

[1] The presented taxonomy is not restricted to visual-only experiences but includes all human senses [23]. Also, any technology other than head-mounted displays (HMDs) can be used to create the visual scene.

[2] The combiner can cause minor distortions and lowers the transmission of ambient light.

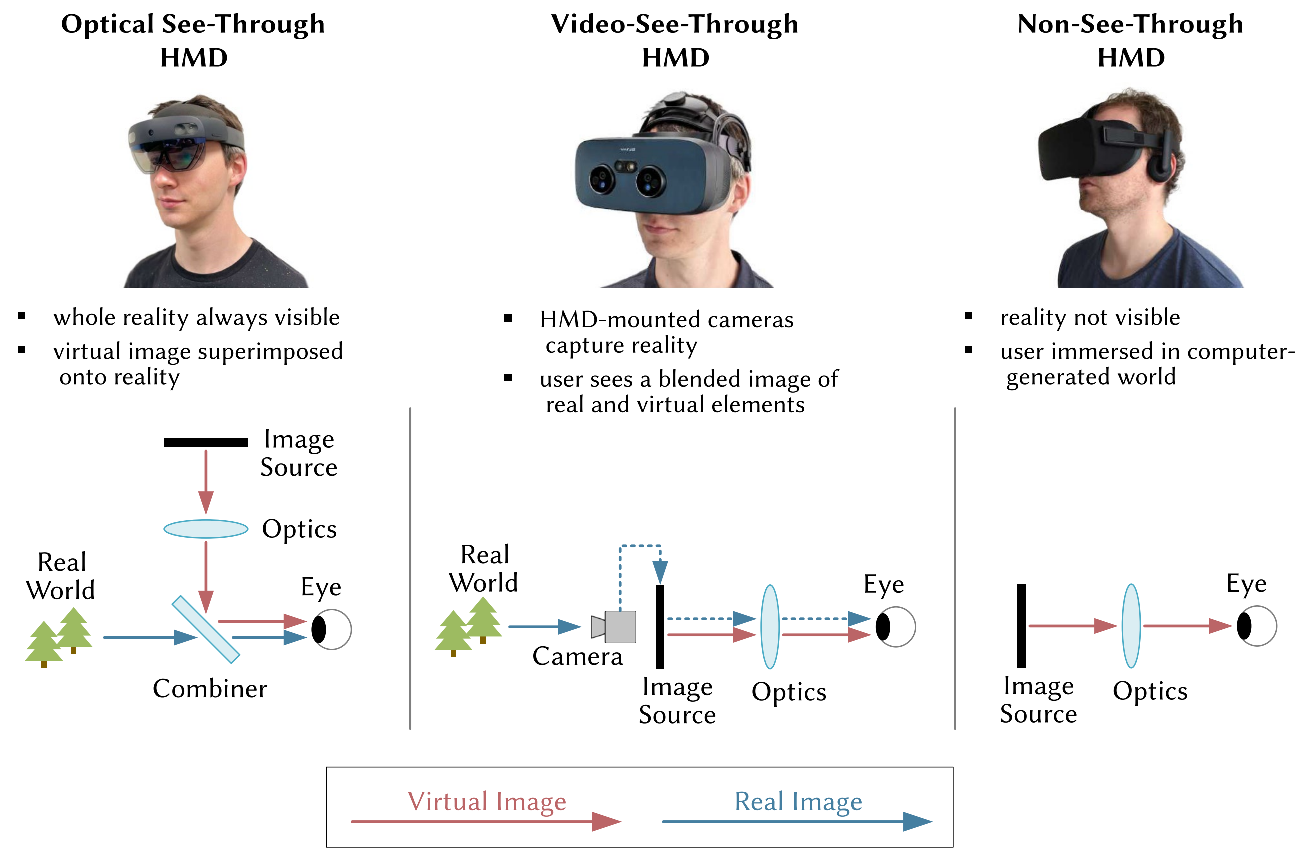


Fig. 2 Different types of HMDs that can be used to create a mixed reality (drawings inspired by [29, 30])

Figure 2 sketches the optical architecture, which is rather similar to VR-HMDs. As depicted, these devices — which are sometimes also called electronic or digital see-through HMD [39, 40] — are usually (but not always [39]) designed as immersive goggles with no direct view of the real world.

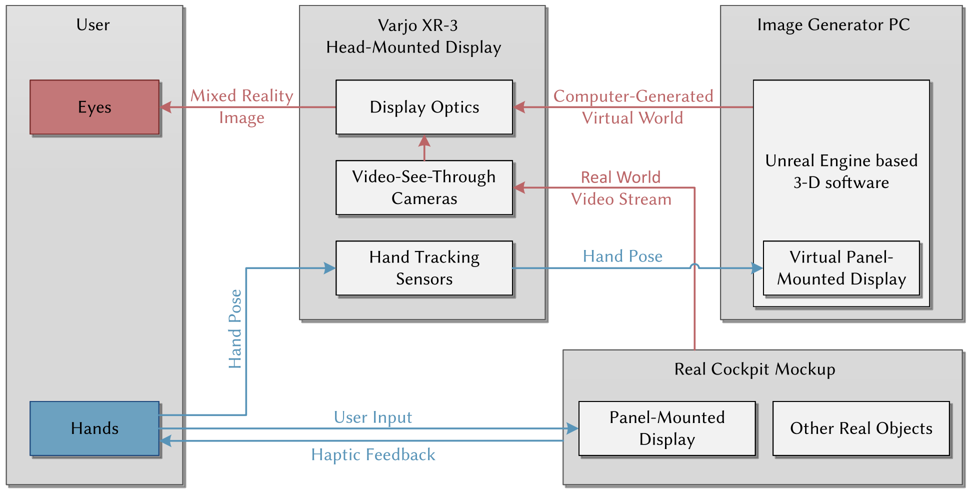
Their big advantage is that embedding virtual content into real-world video produces a considerably better visual experience than the superposition done by optical see-through HMDs. The ambient luminance can be controlled and virtual objects can actually occlude real elements, which results in a far more realistic appearance [30, 40]. Nevertheless, they also have specific challenges: The motion-to-photon latency of the camera images must be very low to avoid disorientation and sickness symptoms [30, 40]. Moreover, camera and display resolution must be high enough and the distortions must be low enough to replicate the reality in sufficient quality [41]. Depending on the use case, the cameras need an adequate or even adaptable sensitivity to be usable in- and outdoors or in bright and dim environments. In recent years, many consumer and enterprise HMDs with video-see-through functionality have been released, for example: Varjo XR-3 [42] (see Fig. 2), Meta Quest 3 [43], HTC VIVE XR Elite [44], and Apple Vision Pro [45].

2 The developed mixed reality air taxi simulator

Within the project "HorizonUAM" we had the goal to implement a highly customizable simulation environment where different cabin arrangements and interface designs can be realized and evaluated quickly and cost-efficiently. We chose a video-see-through (VST)-HMD as it enables us to simulate a near 360-deg out-the-window view without a large dome

Fig. 3 User wearing the Varjo XR-3 inside the air taxi mockup of DLR's XR-Sim

Fig. 4 Information flow between the main modules of the XR-Sim and the user



projection system and at the same time realize natural user interaction.

The developed system does not have a single configuration only, but offers different options for:

(1) the blending of the real with the virtual parts of the environment and
(2) the user interaction with the mixed reality.

As shown in Fig. 3, the setup only includes an air taxi cockpit/cabin mockup and a video-see-through HMD worn by the user — it does *not* include any outside vision projection dome or screen. The mockup represents a generic four-seat air taxi cabin with a size of 1.80 m × 1.58 m × 1.28 m.

For the selection of the VST-HMD, we had three main requirements: high display resolution, adequate wearing comfort, and reasonable value for money. Based on that, we chose the Varjo XR-3 as it was the most appropriate device that was available at the time.

Figure 4 sketches the information flow between the user and the main modules of our mixed reality simulator XR-Sim. The central piece is the Varjo XR-3 [46]. For this setup, its most important feature are the two VST cameras, which capture a video stream of the real world around the user, i.e., the cockpit mockup. An image generator PC then fuses this real-world image with virtual elements, which are generated by 3-D software based on *Unreal Engine 4.27*. As illustrated by the red arrows in Fig. 4, the mixed stream of real and virtual imagery is finally displayed to the user through the HMD's display optics. In our case, the window areas of the real-world stream will be filled with a computer-generated out-the-window view while the rest of the user's field of view will be VST imagery. Implementation details of the blending between real and virtual image are presented in Sect. 2.1. To enable the user to read text or to recognize small details on the panel-mounted display, it is important that both the cameras and the display provide a high-definition image. To reach the required display resolution, the Varjo XR-3 uses optical foveation with an inner $27° \times 27°$ focus display providing a high angular resolution of 70 pixels per degree (PPD).[3] The peripheral area offers around 30 (PPD).

Thanks to the VST cameras, the users can also see their hands and interact with the real cockpit mockup. For instance, they can make inputs on the panel-mounted touch display (see blue arrows in Fig. 4). To interact with virtual objects, we make use of the Ultraleap Gemini hand tracking system which is integrated into the Varjo XR-3. Additionally, the detected hand pose can be used for gesture control or to render virtual doubles of the user's hands (details see Sect. 2.2).

Finally, it is important to note that we can realize different "degrees of mixed reality" with the described XR-Sim. In other words, depending on the selected configuration, the setup can be further left or right on Milgram's reality-virtuality continuum (Fig. 1). For a "more real" setup, we can show major parts of reality via the VST cameras and only add a few virtual elements to the scene. For a "more virtual" setup, we can switch off the VST cameras and render virtual doubles of the user's hands that interact with virtual touch displays. In the latter case, the sole purpose of the real cockpit mockup is to provide haptic feedback when the user touches it. The following Sects. 2.1 and 2.2 will provide more details on the available options.

[3] Humans with normal visual acuity — often referred to as 20/20 vision — are able to resolve one arc minute (1/60 deg), which can be translated to 60 (PPD).

Fig. 5 Blending real and virtual world in DLR's mixed reality flight simulator XR-Sim — view through the user's eyes (**a**) Unmodified real-world video stream captured by the cameras mounted onto the HMD. It shows the cockpit mockup, but also the lab room through the windows (**b**) Real-world video stream blended with virtual out-the window view (solution to wrong occlusion of left hand see Fig. 6)

2.1 Blending the real with the virtual world

The virtual 3-D world is modeled in the game engine *Unreal Engine 4.27*. Within this environment, we also define the areas in which the imagery of the VST cameras should be rendered. In our case, we use a 3-D model of the real mockup to declare a rather complex masking geometry. The result can be seen in Fig. 5. The left image depicts the unmodified video stream of the real surroundings; it shows the physical mockup, the user's body, and — through the windows — the lab room. Figure 5b shows the resulting mixed view of the real and virtual scene which the user finally sees in the HMD. Based on the described 3-D mask, the window areas of the video image are cut out and replaced by the computer-generated environment. This way it looks like the aircraft is standing on a landing pad. The result is rather similar to a conventional flight simulator. However, the setup does not need a complex outside vision projection dome placed around the aircraft mockup to create the virtual out-the-window view. This general setup can now be enhanced with additional virtual elements. For instance, we can adapt the layout of the real cockpit mockup by adding computer-generated objects like virtual displays, seats, et cetera.

2.1.1 Alignment of real and virtual world

One of the biggest challenges of such a setup is that it requires very precise alignment between real and virtual objects. For correct blending, the window frames of the virtual mockup must be located at the exact same location as their counterpart in the real world. Otherwise, the seams between video imagery and virtual out-the-window view will look incorrect. The user may see video areas with parts of the lab room instead of the virtual out-the-window view. Moreover, the same requirements apply for certain interaction techniques described in Sect. 2.2. Incorrect alignment will result in unnatural haptics.

Alignment is usually accomplished by tracking a real-world target whose position is also known in the virtual world. For the XR-Sim, we use the visual marker tracking provided by the Varjo XR-3. We attached two markers to the mockup (one of them can be seen in Fig. 5a), measured their position, and implemented an algorithm that aligns the virtual mockup, which is used for masking the video with the captured position of the real-world mockup. An alternative approach to the visual markers is the usage of a VIVE Tracker [47]. It can be mounted at a defined location on the mockup to deliver pose data for the alignment algorithm. Besides the precise tracking system it is also crucial that the HMD optics are calibrated such that the camera imagery is correctly registered with the real world (no distortions etc.).

2.1.2 Occlusion between real and virtual objects

Closer objects occluding more distant items is one of the most prominent cues for human depth perception. Thus, it is crucial to also reflect this occlusion behavior in a mixed reality environment. However, this requires knowledge about the position of all involved objects. We obviously have the required data about all virtual objects, but the VST cameras deliver a flat image without actual 3-D information about the real world. Thus, it is impossible to implement correct occlusion between real and virtual objects without further data. Figure 6a shows an example: The graphics software cannot know that the user's hand captured in the video is closer to the eyes than the overlapping objects in the virtual world. Actually, it does not even know that these pixels are in the user's hand. Thus, the hand is "cut off" as the rest of the video stream within the window frame (This behavior is defined by the 3-D mask described above).

To get the required hand pose data, we use the skeletal hand mask feature provided by Varjo. This uses integrated hand-tracking to "cut out" the video in the areas where the user's hands are located. Unfortunately, this technique is not very precise leading to the video areas often being slightly larger than the user's hands, which creates visible seams between real and virtual world (see Fig. 6b). Further, this method only works for the user's hands. Correct occlusion behavior of other dynamic real-world objects cannot be implemented with this technique. Alternatively, one can put the whole simulator inside a green room and use Varjo's chroma key functionality to insert the virtual imagery only where the camera captures green areas. This promises better results than the hand-tracking-based solution but comes with the additional effort of setting up a green room.

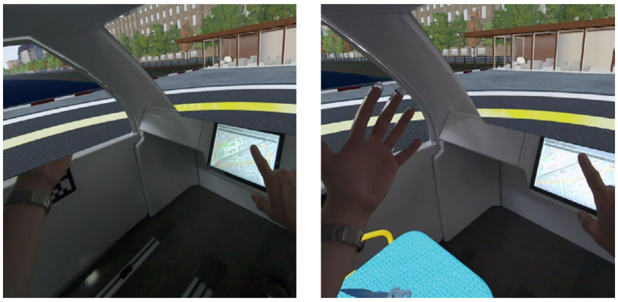


Fig. 6 Hand masking to avoid wrong occlusion between the user's hands and virtual elements (**a**) Hand masking off — The user's left hand is hidden by the virtual out-the-window view because no information about the depth of the objects captured by the video cameras is available (**b**) Hand masking on — Correct occlusion between hand and virtual scene based on hand position data provided by the Ultraleap hand tracking. However, the blending of virtual scene and realworld video stream is not precise enough to avoid visible seams between both domains

2.2 Interacting with the mixed reality

A central part of a flight simulator is the human–machine interface, which on the one hand outputs information to the users and on the other hand enables them to make inputs to the system. To do so, a cockpit comprises various types of input devices: flight controls, push buttons, dials, toggle switches, 4-way switches, and different cursor-control-devices (thumb-/fingerstick, trackball/-pad). Replicating these in a mixed reality environment poses a major challenge. Five common techniques are compared in Table 1 and described in the following paragraphs.

2.2.1 Finger-tracking-based methods

The fully virtual approach has no real input hardware; it only shows virtual user interfaces via the HMD. A button press is detected via a finger-tracking system (e.g., [48]). This leads to a very flexible, easily re-configurable user interface. However, the main problem of virtual-only input devices is the absence of a counter-force and the missing natural haptic feedback. Pressing a physically not existing button is not intuitive and makes a trivial task unnecessarily complicated. Thus, Schiefele et al. [49] implemented a simple feedback mechanism by mounting flat plastic panels at the button locations such that the pilots felt when they reached the button. Of course, this takes away the ability to easily change the virtual user interface, e.g., for rapid prototyping of another instrument setup. Further, the haptic experience is limited to pressing onto a flat surface. A solution to this can be haptic gloves. They apply various techniques, from simple vibrations [50] to light-weight exoskeletons [51] and microfluids [52], to generate a natural feeling of touching a virtual object. This approach promises to provide a higher degree of realism while still allowing to instantaneously change the virtual cockpit interface. Unfortunately, such concepts are still under development, even though the current device generation seems to come closer to meeting the high expectations of that technology.

2.2.2 Methods based on real input devices

The most realistic user interaction is generated by using real input devices (stick, touch display, etc.). These receive the user's inputs and provide haptic feedback, while the HMD shows a visual representation of the input hardware. The physical input devices can be made visible via two different approaches: First, one can place a computer-generated model of the input device in the exact same position in the virtual scene. This way, the user sees a fully virtual environment but feels and interacts with real hardware, which is aligned with its virtual counterpart (e.g., [12, 36]). An alternative approach is to use a video-see-through HMD which shows a video stream of the user's hands and real input hardware integrated into the otherwise virtual world. This is believed to appear more realistic than entirely computer-generated visuals as described before.

Table 1 Comparison of different approaches to replicate common hand/finger interaction paradigms in a mixed reality simulator (detailed descriptions in the text and the cited references)

	Input	Visual Representation	Perceived	Flexibility of the	Example
Fully virtual	Finger-tracking	Computer-generated	Low[a]	High	[48]
Feedback panels	Finger-tracking	Computer-generated	Rather low[b]	Medium[c]	[49]
Haptic gloves	Finger-tracking	Computer-generated	Medium[d]	High	[50–52]
Mixed setup	Real input device	Computer-generated	High	Low/medium[e]	[12, 36]
Video-see-through	Real input device	Real[f]	High	Low[e]	[22]

[a] No haptic feedback provided

[b] Haptic feedback from plates is rather limited and unspecific

[c] Feedback panels are at fixed locations

[d] Technology under development, first devices demonstrate high potential

[e] Real input hardware is at fixed locations. Non-interactive/virtual parts can be changed easily

[f] Via video stream from the VST cameras

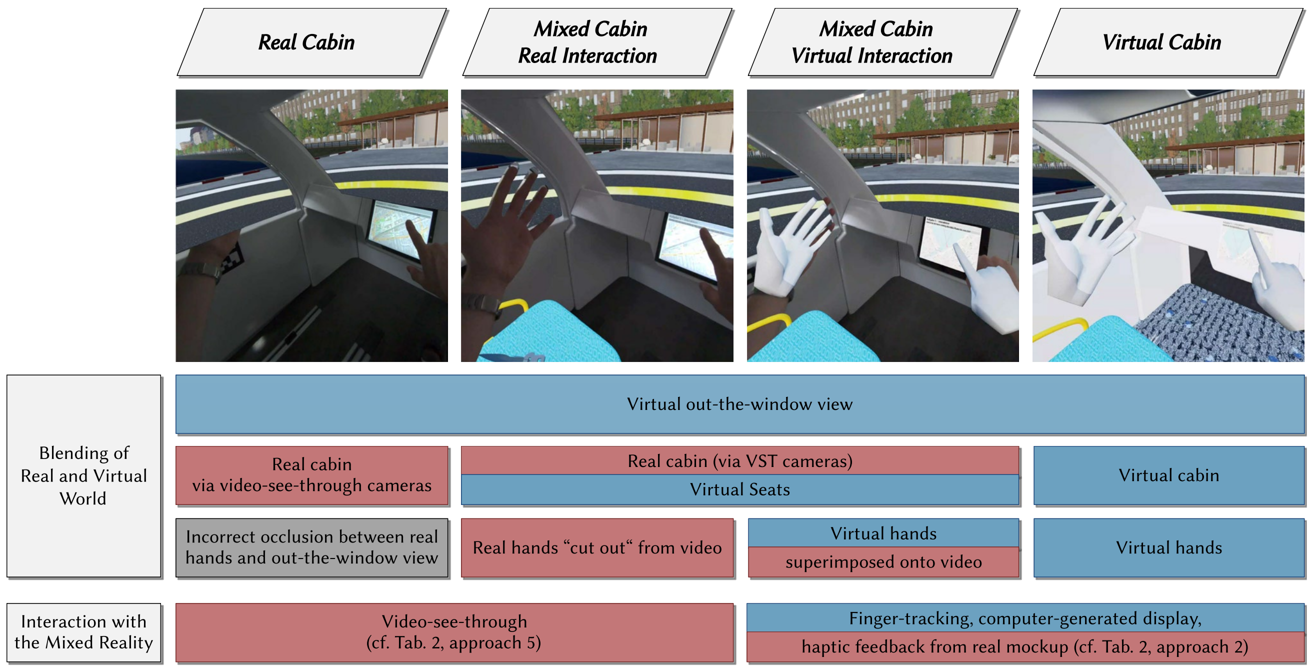


Fig. 7 Overview of the setup variants that were implemented in DLR's XR-Sim and evaluated in the user study

Obviously, the higher interaction fidelity of these two methods is paid for with lower flexibility.

In summary, one can state that the selection of a suitable interaction approach appears to be a trade-off between realism and flexibility of the user interface. Increased realism of the interaction is usually paid by a less flexible hardware setup.

3 User study to compare the various setup variants

To evaluate which of the potential approaches described in Sect. 2 is best-suited for human-in-the-loop studies on air taxi passenger acceptance, we conducted a first parameter study. Our human-in-the-loop experiment compared four pre-selected setups with a focus on the visual representation of the mixed reality and the respective user interaction experience. This section first describes the adopted methodology and then summarizes the key findings. For supplementary results one can refer to [22].

3.1 Method

3.1.1 Participants

Twelve subjects — nine male and three female — participated in the experiment. Their age ranged from 23 to 48 years (median age: 35.5 y). Their experience varied from 0 to 50 h for VR (median: 10 h) and from 0 to 100 h for AR and MR (median: 5 h). Five subjects stated that they used hand-tracking systems before. The experiment was conducted in their native language, which was German for all participants.

3.1.2 Tested setups

As described in Sect. 2, the developed simulator offers many different options for the configuration of the mixed reality. Figure 7 shows the variants that were compared as independent variables in the study. The four setups can be distinguished in (a) how the blending of the real and virtual world is realized (see Sect. 2.1) and (b) how the interaction with the mixed reality happens (see Sect. 2.2).

3.1.2.1 Mixed Reality Blending All four options include a virtual out-the-window view. The first — called *Real Cabin* (RC) — shows the physical cabin mockup via the VST cameras while both *Mixed Cabin* options augment the VST cabin view with virtual-only elements like the virtual seat that can be seen in the images. The fourth variant, *Virtual Cabin* (VC), has a computer-generated visual representation of the cabin, which means that the user's whole view is virtual. The physical cockpit mockup cannot be seen but — as it is aligned with its virtual counterpart — it can provide haptic feedback. Furthermore, various visualization techniques for the user's hands were tested. RC just shows the real hands in

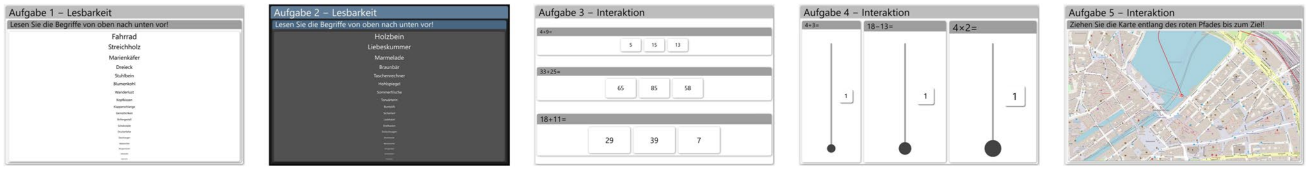


Fig. 8 The test displays used to evaluate readability and interaction with the user interface in the different conditions [22] (Reprinted with permission, ©2022 IEEE)

the video stream without hand masking to avoid the incorrect occlusion behavior due to missing depth information (see Sect. 2.1 and Fig. 5 for details). *Mixed Cabin – Real Interaction* (MCVI) avoids these occlusion issues by "cutting out" the hands from the video stream. *Mixed Cabin – Virtual Interaction* (MCVI) superimposes the VST imagery with virtual hand models based on hand-tracking data and the last condition, VC, has the same virtual hand models but within its virtual cabin view, which entirely avoids occlusion problems.

3.1.2.2 Interaction The implemented variants do not only differ in the blending of real and virtual but also in the way how the hand–display interaction is realized. In our study, we looked at different types of interaction with a panel-mounted touch display, i.e., button press, slider input, and pan a map. Our first two setups, RC & MCVI, resemble option five in Tab. 1. The users see their real hands via the VST cameras and naturally interact with the real touch display mounted in the cockpit. By contrast, the two other setups, MCVI & VC, show a computer-generated display placed at the same location. The hand tracking data provided by the Varjo XR-3 is used to render the virtual hand representations and to detect user inputs. Since the virtual display is aligned with the real cockpit panel, the users receive haptic feedback when they touch the screen. This setup is similar to the second approach in Tab. 1 — with the difference that, for a touch display, providing the haptic feedback through a simple panel is not as unrealistic as using this option for knobs or other more complex input methods.

3.1.3 Experimental design

The experiment applied a within-subject design with the mixed reality setup described above as the only independent variable. After an initial briefing and a biographical questionnaire, the participants completed two distinct test blocks of about 40 min with a 10-minute break in between.

During the first block, the air taxi remained on the ground as the focus was to compare the developed setups with respect to readability and ease of interaction with the passenger information display. The participants were prompted to read words in light and dark mode, to press buttons, to move sliders of varying sizes, and to pan a map, all shown on the display in front of them. Figure 8 shows the displays used for testing. After each type of interaction, they had to rate their experience. Additionally, statements regarding hand visualization and a possible mismatch between real and virtual hands had to be rated. Finally, the participants had to rank the setups according to their preferences.

In the second test block, four flights in an automated air taxi were simulated — one flight per setup, counterbalanced between the participants. Each flight started from a fictional vertidrome located on the Binnenalster in Hamburg (Germany) and took five minutes: Climbing to a cruise height of 500 ft above the Binnenalster and following along tracks of the metro line towards Hamburg airport. During the flight, the participants were allowed to explore the entire environment including out-the-window view, cabin visualization, and passenger information display. Afterwards, the appeal of the mixed reality experience was assessed.

After all flights were completed, a debriefing questionnaire aimed to assess the overall usability of the simulator, the appearance of the urban scenery, the perception of flight movements and air taxi sounds, as well as the visual and the wearing comfort of the HMD. The total experiment duration was about two hours.

3.1.4 Apparatus

The study was conducted in the XR-Sim described in Sect. 2. The 3-D model of the urban environment was created in-house by fusing data from various sources. We used Trian3DBuilder to create a terrain surface textured with orthophotos as well as auto-generated buildings based on OpenStreetMap data. These were then imported to Unreal Engine 4.27 via its Datasmith plugin. As the auto-generated buildings were not realistic enough for areas where the air taxi operates close to the ground, we modeled more detailed buildings by hand with the 3-D graphics software Blender. Furthermore, both vertidromes depicted in Fig. 9 were designed and modeled like this.

Flight and aircraft state data was provided by X-Plane through a replay of a pre-recorded flight. The data was sent via the message broker RabbitMQ and received by a client implementation in the graphics engine. Moreover, the

Fig. 9 The vertidromes designed and modeled for the simulation of an air taxi flight in Hamburg. Both landing spots do not exist in reality but were created for research purposes [22] (Reprinted with permission, ©2022 IEEE) (**a**) Vertistop at Hamburg Binnenalster (**b**) Vertiport at Hamburg Airport

message broker was also used to control the involved programs from a controller user interface on the experiment control PC.

The graphical user interface of the passenger information display was designed as scalable vector graphics in Inkscape which is injected into an HTML page via an in-house developed framework. This also implements functionality for the display of external data and basic inputs like buttons, sliders and knobs. As a map rendering engine we used OpenLayers to show OpenStreetMap image tiles. A detailed description of the developed passenger information display is found in [53, 54].

3.2 Results

In the following, findings related to visual representation and blending between reality and virtuality are described first. Afterwards, those related to hand–display interaction are presented.

3.2.1 Visual representation and blending

To assess the experienced level of immersion, the participants were asked if they felt like inside a real air taxi cabin after they have seen all four developed setups. Figure 10 shows that all setups reached a median approval rating of 4 (= rather agree). However, the setups incorporating a video-see-through visualization of the air taxi cabin were rated slightly worse than the fully virtual representation. A reason for this could be the noisy imagery of the VST cameras, which results in lower image quality and thus affects the realism of the scenario. The noise is caused by the low light situation inside the air taxi cabin. Placing bright diffusive light sources inside the cabin could mitigate the problem.

Besides the visual appeal of the air taxi interior, the visualization of the environment as well as the realism of flight movements and sound play a vital role to achieve a high level of immersion in a flight simulator. Figure 11 shows box plots of ratings targeting to measure these aspects. While the participants largely agreed that the city could be identified as such (first statement) some of them also found visible inconsistencies to be distracting (second statement). As buildings and trees were auto-generated from OpenStreetMap data the realism is limited due to an inconsistent or incomplete database but also by repeating or inapplicable textures (i.e., not fitting to the building's purpose or the European architectural style).

The third and fourth statements of Fig. 11 aim at the realistic simulation of flight movements. The box plots show that the participants rated the plausibility and their tolerance towards the prevalent dynamics with good to very good. These results have to be taken with care, though, as the dynamics could only be perceived visually and not through mechanical stimuli. As X-Plane 11 does not feature any flight model of an eVTOL a flight model of an Airbus H135 helicopter was used.

The last two box plots are related to the sound that was noticeable during the simulated air taxi flights. It came from a 2.1 sound system installed in the back of the mockup playing the H135 sound directly from X-Plane. The volume was approximated because no reliable information on the cabin noise level of air taxis was available. Despite these circumstances, the majority of participants agreed or rather agreed

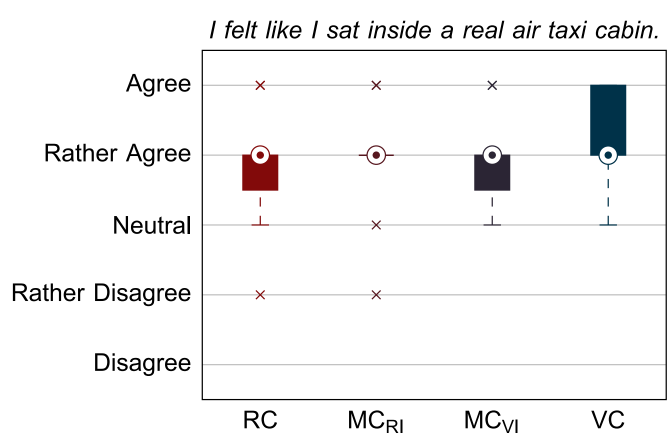


Fig. 10 Comparison of the perceived realism of the tested setups. The box plots show median (dot/circle), 25th and 75th percentiles (filled rectangle), and outliers (x markers) with whisker length 1.5 interquartile range [22]

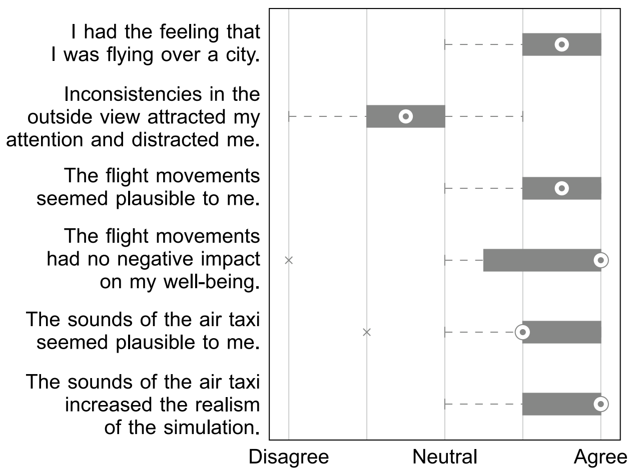


Fig. 11 Ratings of outside vision, flight simulation, and sound [22]

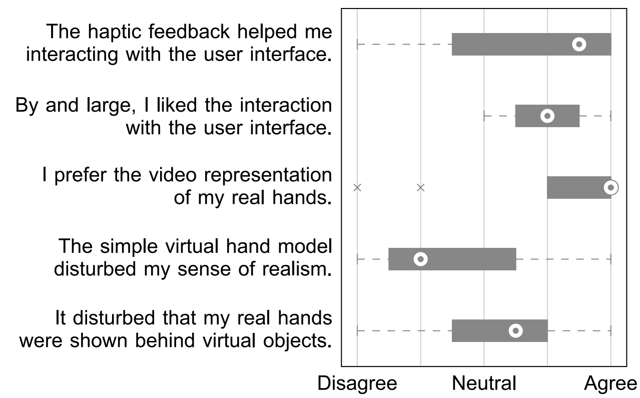


Fig. 12 Ratings of the hand–display interaction in the different setups [22]

that the sounds seemed plausible and even more thought that it increased the realism of the flight simulation.

3.2.2 Hand–display interaction

Section 2.2 already pointed out a detailed overview of the possibilities to interact with mixed reality. In the conducted study, two of the five interaction modalities were compared: Interaction with feedback panels and interaction with a real tablet computer via VST. RC and MCVI implement the VST variant, MCVI and VC feature feedback panels (cf. Figure 7).

To receive an overall rating regarding ease of interaction, the participants were asked to mark every setup with a school grade, with 1 being the best and 5 the worst. From the three tested setups, RC got grade 1 from 7 of 12 participants and grade 2 from the remaining 5 participants resulting in an average grade of 1.4 and therefore being the most liked one — MCVI was not tested because its interaction does not differ from RC. MCVI and VC were rated worse with average grades of 3.2 and 2.7, respectively.

This distribution may be induced by conflicting information from the user's visual and haptic senses due to inaccuracies in object, head and hand tracking. As can be seen from the first statement of Fig. 12 the haptic feedback helped a major portion of participants to interact with the user interface (UI). Although the tablet computer provides haptics in all setups the alignment of it with the virtual UI in MCVI and VC deviated by a few millimeters. That might already have evoked confusion as sometimes an interaction was not detected even though intended and vice versa. This issue together with the strong preference for the VST image of the real hands (third statement) can be a reasoning why the real interaction has been rated better than interacting with the virtual user interface.

As can also be seen from Fig. 12 there is discord among the respondents about the disturbance of the virtual hand models (fourth statement). While the box plot shows a slight trend that there was no disturbance from the virtual hand representation a large proportion remarked in the comments that there was a mismatch between virtual and real hands or that finger tracking could not always follow the hand movements. This can also be a reason for the disagreement to the fifth statement between the participants. The aforementioned mismatch led to confusion which of the two shown hands — virtual model or VST image of the real hand — triggers the input on the UI.

From the results can be concluded that participants overall liked the interaction through VST (i.e., the one more close to reality) more than relying on the virtual UI as interaction is more precise and provides more accurate haptic feedback. The interplay of tracking different objects — like the HMD is tracked from external tracking units, HMD-integrated cameras track markers for virtual UI positioning and additional HMD-integrated Ultraleap tracking units track the hands' movements — induces multiple errors that add up and can make the system unreliable.

This section summarized the most important findings from the conducted study. For an extensive description of the study and additional results, please refer to [22].

4 Reception of the simulator during its first application in a passenger acceptance study

Based on the results of the study described above, the simulator was further enhanced and finally used for a study that focused on various aspects related to user acceptance of future air taxi operations: What is the influence of one person belonging to the aircrew being on board on the experience of the air taxi flight? How do participants experience the active interaction with the aircrew in a rerouting situation?

How do participants experience typical flight maneuvers of an air taxi, especially takeoff, landing, climbs and descents and turns? How do participants experience the information regarding the flight status? While Papenfuss et al. [54] thoroughly discuss these user acceptance questions, this paper concentrates on all findings regarding the MR simulation environment. In particular, this section answers the following questions:

- How was the the MR setup received by the participants and what implications does it have on the study design and execution? (R1)
- Does the simulation experience influence the participants' attitude towards UAM and air taxis? (R2)

4.1 Method

4.1.1 Participants

The study was conducted with 30 participants, 14 female and 16 male. The sample's age (mean: 41, standard deviation: 18) was quite heterogeneous with slightly overrepresented young people compared to the general public (detailed sociodemographic profile see [54]). The subjects had a rather positive attitude towards both aviation and technology in general (mean 7.73 (both), standard deviation: 2.29/2.28 on a 10-point Likert scale with 10 representing high interest, measured before the study). The experiment was conducted in the native language, which was German for 29 and English for one participant.

4.1.2 Apparatus

For this study, we used the XR-Sim as described above but implemented a combination of the conditions RC and MCVI from the previous study (see Fig. 7). The main reason for this decision was that the participants preferred to interact with the touch display using and seeing their real hands (via the VST cameras) — in contrast to the virtual-hand interaction method used in MCVI and VC (see Sect. 3.2.2). Regarding the blending of the real and virtual world, the participants saw a VST image of the real cabin mockup augmented with virtual seats (cf. MCVI). As the rather inaccurate "cut out" and blending of the real hands with the virtual out-the-window view was found disturbing in the previous study, we decided to disable this feature and accepted the incorrect occlusion when the participants held their hands in front of the windows (cf. RC, Fig. 6a). Furthermore, the criticized video quality was improved by increasing the light setting with a softbox and additional lights placed inside the cabin.

The panel-mounted touch display showed a passenger information display. It was specifically developed to inform the air taxi passengers about the flight status and connecting flights at the destination. Moreover, it provided an interface for voice interaction with the control center on ground. More details can be found in [53, 54].

During the study preparation, we realized that the user's restricted peripheral vision (caused by the HMD) significantly limits the perception of objects or persons next to them. In our case, we had to carefully plan the seating arrangement to ensure that the presence of the accompanying flight attendant was perceived by the participant without requiring them to actively turn their head to the side.

4.1.3 Experimental design and procedure

The results described in this work were gathered as part of a larger study, which comprised two consecutive parts: a within-subject experiment with the factor "presence of flight attendant" (yes, no) in a regular flight, followed by a between-subject experiment with the same factor, however, in a non-nominal flight where a re-routing took place. The between-subject design for the latter was chosen to have the non-nominal situation occur only once per participant. This should account for the typical unexpected character of such an event. Note that the design of the experiment and its independent variables was primarily defined by the requirements of the user acceptance research mentioned in the introduction of this section (details see [54]). The two research questions considered in this paper (see bullet list above), were addressed through repeated measurements across both parts of the study, as described below.

The study started with a briefing on UAM, study purpose, and procedure followed by a hands-on introduction to the simulator. Afterwards, the participants experienced four flights in the air taxi: one familiarization flight, two regular flights — one with accompanying flight attendant, the other unaccompanied (in balanced order between subjects) —, and finally one non-nominal flight with or without flight attendant (between-subject part of the experiment as described above). Each flight simulated a 10-minute airport shuttle service along the same route from the city center to the airport of Hamburg, Germany. Several findings from other works within DLR's HorizonUAM project influenced the layout and locations of the vertidromes [55] as well as the route selection, which was planned to not interfere with regular air traffic routes at the airport [56].

As part of research question R1, an instantaneous self-assessment of individual well-being was presented on the panel display of the air taxi at eleven different times during each flight. It comprised a 5-point Likert scale from 1 representing "uneasy, worried, nervous" to 5 being "comfortable, relaxed, safe". The participants were not instructed to focus on a specific aspect such as flight maneuver or simulator, but to rate their *general* well-being. Moreover, a questionnaire addressing the participants' attitude towards air taxis was filled out before and after the flight experience (cf. R2). Additional questionnaires and interviews concerning R1, R2, and the mentioned user acceptance research were conducted after each flight and at the end of the study. The total experiment duration was between 2.5 and 3.5 h.

4.2 Results

4.2.1 Reception of the MR simulation

Overall, the developed MR simulation was received positive by both the study participants and the experimenters. Even though the participants did not directly rate the simulator, they answered an instantaneous self-assessment of general well-being. On the 5-point Likert scale, the maximum/best rating was given in 77 percent of the cases. In contrast, the two lowest ratings were given in less than 2 percent of all events. Because of technical issues, 3 percent of the ratings are missing.

Aside from the simulator, for the assessment of passenger acceptance, a detailed analysis of how the well-being ratings varied based on the factors "company of flight attendant" and "type of flight maneuver" is conducted by Papenfuss et al. [54].

Asked about their experience, 2 of 30 participants reported discomfort or problems caused by the HMD or the simulation. Likewise, four mentioned the HMD when directly asked about discomfort. In particular, they stated that head movements were uncomfortable, the out-the-window view was distorted, and the image was jerky during turns. Finally, the sounds appeared to cause discomfort for three participants. In addition, one could observe that a few participants took longer breaks between the flights than others to mitigate discomfort issues. Nevertheless, no one had to abort the experiment because of discomfort issues.

Asked about desired changes, one-third of the participants named the simulation. The most frequent request was a more detailed simulation (seven participants) while other requests like more noticeable movement, more air traffic, more varying air traffic, and better service call quality were raised by only one participant respectively. Interestingly, the restricted peripheral vision through the HMD, which caused us to re-plan the seating arrangement of the flight attendant during the study preparation (cf. Sect. 4.1.2), was not mentioned as an issue by any participant.

4.2.2 Effects of the simulation on the attitude towards UAM

The participants' attitude towards air taxis and UAM was assessed before and after experiencing the simulator flights. The results show that it changed in 22 of 30 cases: 21 participants rated their attitude towards UAM to be more positive, whereas one reported a negative change. For the remainder, no changes were measured. In the interviews, they pointed out that during the course of the study they could familiarize themselves with the procedure of flying in an air taxi, leading to a more relaxed feeling towards the concept. Also, they rated more use cases for air taxis as realistic. However, a few participants were more skeptical regarding the overall concept of air taxis, but not with regard to their personal experience. The only participant that gave a more negative rating after the simulation experienced the flight as frightening and uncomfortable. Especially the vicinity to buildings and the experience of turn maneuvers caused concerns. Also, a relation to MR discomfort is likely in this case.

5 Discussion and conclusion

A successful implementation of UAM is expected to — among others — depend on public acceptance and user adoption [3, 6]. The authors follow a user-centered design approach to address these important factors as early as possible in the development of UAM systems. This work shows how an MR air taxi simulator can help to reach this goal by making future air taxi operations tangible, even in early development stages, and at the same time giving researchers great flexibility to rapidly implement their experimental setup. The following section discusses our major findings from two human-in-the-loop studies, argues where the MR simulator can be useful in the future and where conventional approaches might be the better option, and concludes with an outlook on future directions.

5.1 Development of a suitable MR setup

The first study (see Sect. 3) compared four MR setups with different combinations of real and virtual elements. Overall, all tested variants received good ratings. The participants stated that the immersion and the perceived realism were high for all setups, with slight advantages for the virtual cabin representation. This opinion was mainly caused by the weaknesses of the VST variants: First, the quality of the video imagery was negatively affected by the light setting inside the cabin mockup. Second, the visible seams between the areas of the real and the virtual image degraded the feeling of immersion and realism.

Regarding the interaction, the users favored the real touch display over the virtual setup. The main reason was that the virtual interaction appeared to be less precise, which made especially the sliders and the map difficult to use.

Analyzing these results, we can conclude that the creation of such an MR simulator involves two major challenges:

1) The computer-generated scene needs to be perfectly mapped onto its real-world counterpart.
2) Correct occlusion behavior between elements of both worlds must be ensured.

The precise reality–virtuality alignment is crucial for both interaction and blending. In this respect it is important to note that this requires not only a highly accurate head, finger, and object tracking system. Equally important is the calibration of the VST-HMD, which must ensure that the video stream of the real world is aligned with the computer-generated scene. The users feel the actual real world but see it only through the VST cameras.

Ensuring correct occlusion behavior between elements of both worlds requires precise and dynamic knowledge about the depth of the real scene. Without appropriate sensors, one can, for instance, not make the user's hands appear in front of virtual elements — they will just be hidden behind them.

Regarding hand and object tracking, the closer the user gets to objects, the more accurate it must be. In such cases, also shadowing effects will play an important role. For instance when grabbing a real object, some fingers may be invisible for an HMD-mounted sensor as they are hidden behind the object.

5.2 Applicability to user acceptance research

The acceptance study showed that the developed MR air taxi simulation had the power to give participants who are inexperienced in UAM a better impression of the concepts. The results in Sect. 4.2.2 reveal that it could even change their attitude towards air taxis in 73 percent of the cases. Likewise, the simulated re-routing of the air taxi was perceived as more annoying and uncomfortable than the planned flight. This result could be seen as an evidence that the simulation setup may even be so immersive that study participants expressed realistic emotions like frustration. Consequently, it appears to be a useful tool to build or sharpen an opinion about UAM concepts. Still, the interviews showed that more detailed 3-D graphics of the surroundings could probably even improve the participants' immersion and perceived realism.

The results regarding well-being let us conclude that — in the majority of the cases — the simulation environment did not negatively influence the participants' comfort and thus did not interfere with the research goal. The general well-being rating gave very positive results. Additionally, most participants did not report any discomfort caused by the simulation in general or the HMD in particular and no one had to abort the experiment due to MR sickness issues.

Even though the majority experienced no discomfort, we received a few mentions of such problems. For one participant it is even likely that the negative change in their attitude towards UAM and the undergone comfort issues were related. Thus, it is important for future studies to consider this already during the planning phase by limiting the exposure time. Also, our studies showed that allowing breaks whenever necessary was well received and helped a number of participants to mitigate discomfort.

Another issue that can have implications on the design of future studies is the fact that the HMD restricts the perception of the environment through peripheral vision. Thus, objects and persons next to the study participant might not be perceived as in a non-MR setup.

5.3 Chances and limitations of MR simulation

In summary, the developed MR air taxi simulator was perceived as a fruitful tool to investigate acceptance aspects. Alternatively, a pure VR setup without the cabin mockup would be very portable and could therefore be used to get more participants by moving the study out of the lab to public places where many people come by. As our first study showed, this only works if no complex user interaction is required. However, if one considers this limitation during the design of the experiment, this can be a valid approach for many public acceptance studies.

By contrast, an MR-approach is the first choice for further shaping human–machine interface concepts for passengers in highly automated transport systems. We expect that investigations on user interaction in highly automated or even autonomous air taxis will be a major research topic that can be addressed in such a simulator setup. It provides great flexibility for rapid prototyping of new designs and can involve potential users and their needs and opinions in the design process from the beginning. In our opinion, this has the potential to lower the development costs and at the same time to increase the usability and acceptance of urban air mobility.

A final takeaway from the conducted studies is that the developed simulator is not an optimal setup to test how passengers experience flight maneuvers. First, as a fixed-base system it can only deliver an incomplete experience (no vestibular motion cues). Second, if discomfort or sickness occur, they cannot be attributed to their definite cause: The symptoms may be caused by the tested flight maneuver but could also come from the simulation

(MR-HMD, fixed-base simulation). Thus, no occurrence of sickness symptoms does not guarantee that this might not be an issue in reality. And vice versa, sickness symptoms in the simulator does not necessarily mean that the user will have problems in actual flight. Advanced research on such flight dynamics topics will therefore certainly need a highly sophisticated (non-MR) motion simulator or actual flight tests. An example of such a study are the experiments that Adelstein et al. [57] conducted in NASA's six-degree-of-freedom Vertical Motion Simulator to assess passengers responses to different large-scale motion exposures.

5.4 Future directions

Future work should focus on adapting and enhancing the simulator capabilities to conduct even more valuable human factors studies. For instance, the integration of the XR-Sim onto a motion platform is currently ongoing. Moreover, we also validate alternative hand and finger tracking solutions (e.g. haptic gloves or camera-based full-body tracking) to assess if we can implement a flexible interaction system that feels as realistic as interacting with real input hardware. Finally, an evaluation of the impact of the virtual hand visualization on the perceived realism and interaction performance is planned.

At the same time, we also evaluate how MR/VR-HMDs can be used not only as simulation means but as an assistance system in an actual helicopter cockpit [21, 58, 59]. For example, DLR's project EASINESS will research and develop an onboard control station for escorting UAV. In this military scenario, the UAV operator will sit inside a helicopter and wear a video-see-through HMD to interact with the UAV via an MR interface.

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Declarations

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Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the German Aerospace Center.

Informed consent Informed consent was obtained from all individual participants involved in the studies.

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