Aircraft Cockpit Interaction in Virtual Reality with Visual, Auditive, and Vibrotactile Feedback

STEFAN AUER, University of Applied Sciences Upper Austria, Austria and University of Konstanz, Germany
CHRISTOPH ANTHES, University of Applied Sciences Upper Austria, Austria
HARALD REITERER, University of Konstanz, Germany
HANS-CHRISTIAN JETTER, University of Lübeck, Germany

Fig. 1. Our study compared a full-scale physical cockpit of a Boeing 737-800NG that was part of a flight simulator (left) to an exact replica in a virtual reality flight simulator including visual, auditive, and vibrotactile feedback (right) to understand how well current virtual reality technologies can simulate such safety-critical interactive spaces with many physical controls.

Safety-critical interactive spaces for supervision and time-critical control tasks are usually characterized by many small displays and physical controls, typically found in control rooms or automotive, railway, and aviation cockpits. Using Virtual Reality (VR) simulations instead of a physical system can significantly reduce the training costs of these interactive spaces without risking real-world accidents or occupying expensive physical simulators. However, the user's physical interactions and feedback methods must be technologically mediated. Therefore, we conducted a within-subjects study with 24 participants and compared performance, task load, and simulator sickness during training of authentic aircraft cockpit manipulation tasks. The participants were asked to perform these tasks inside a VR flight simulator (VRFS) for three feedback methods (acoustic, haptic, and acoustic+haptic) and inside a physical flight simulator (PFS) of a commercial airplane cockpit. The study revealed a partial equivalence of VRFS and PFS, control-specific differences input elements, irrelevance of rudimentary vibrotactile feedback, slower movements in VR, as well as a preference for PFS.

Authors' addresses: Stefan Auer, stefan.auer@uni-konstanz.de, University of Applied Sciences Upper Austria, Hagenberg, Austria and University of Konstanz, Konstanz, Germany; Christoph Anthes, christoph.anthes@fh-hagenberg.at, University of Applied Sciences Upper Austria, Hagenberg, Austria; Harald Reiterer, harald.reiterer@uni-konstanz.de, University of Konstanz, Konstanz, Germany; Hans-Christian Jetter, jetter@imis.uni-luebeck.de, University of Lübeck, Lübeck, Germany.

2573-0142/2023/12-ART445
https://doi.org/10.1145/3626481

CCS Concepts: • **Computing methodologies** → **Simulation evaluation**; *Interactive simulation*; • **Human-centered computing** → **Virtual reality**; *Human computer interaction (HCI)*; User studies; • **Software and its engineering** → *Virtual worlds training simulations.*

Additional Key Words and Phrases: Aviation, Pilot, Flight Simulation, Cockpit, Training

ACM Reference Format:
Stefan Auer, Christoph Anthes, Harald Reiterer, and Hans-Christian Jetter. 2023. Aircraft Cockpit Interaction in Virtual Reality with Visual, Auditive, and Vibrotactile Feedback. *Proc. ACM Hum.-Comput. Interact.* 7, ISS, Article 445 (December 2023), 24 pages. https://doi.org/10.1145/3626481

1 INTRODUCTION

Interactive spaces are work environments that integrate multiple connected computing devices, e.g., different digital inputs, controllers, and information displays inside a physical space [20]. Typically, they are intended to support creative or knowledge work inside meeting rooms, design studios, visualization labs, or libraries equipped with multiple mobile screens, interactive tabletops, or other large interactive surfaces, e.g. [20, 51]. In contrast, our more recent research is concerned with *safety-critical interactive spaces* for supervision and time-critical control tasks which are typically found in control rooms or automotive, railway, and aviation cockpits. They are usually characterized by a large number of small displays and physical controls such as switches, buttons, or dial knobs (see Fig. 1, 4).

This reliance on physical controls results in much greater effort and costs for their technical implementation or physical prototyping. Using virtual reality (VR) simulations instead of physical systems could substantially reduce these costs, particularly when using inexpensive, consumer-grade, and off-the-shelf VR hardware. For example, one potential use of VR is enabling rapid testing of new cockpit designs [25] and control layouts without building costly physical mockups [19, 31, 32]. Another is using VR as a cost-effective and portable training supplement for safety-critical procedures without risking real-world accidents or occupying a high-end physical flight simulators (PFS) [55] with acquisition costs of USD 1 Mio or above and operational costs of USD 400-500 per hour [5].

However, previous research has shown that currently available off-the-shelf VR products are generally not well-suited to simulate frequent interactions with many different physical cockpit elements [5]. For example, for some aviation tasks, a virtual reality flight simulator (VRFS) based on an exact replica of an aircraft cockpit using simple, off-the-shelf consumer VR can create a training experience that is already equally successful as real-world training inside a fully-fledged physical cockpit in a high-end, professional PFS. However, using VR comes at the cost of much slower task completion, increased perceived workload, and increased simulator sickness, primarily due to cumbersome interactions with simulated VR cockpit controls [5]. Our work is therefore concerned with the following questions: *How can we employ current commercial, off-the-shelf VR technologies for a cost-effective simulation of interactive spaces that contain many physical controls? How can we do this while minimizing the negative effects of the often cumbersome interactions with such simulated switches, buttons, or dials in VR by better interaction design?*

In this article, we report our results from a user study in which we used a commercial, off-the-shelf VR head-mounted display (HMD) and data glove for finger and hand tracking for three different feedback methods (i.e., acoustic, haptic, and acoustic+haptic) to improve users' interactions with simulated cockpit controls in VR. Thereby, the data glove enabled a controller-free detection of natural hand and finger motions outside the users' field of view (FOV) for mimicking real-world interactions with physical controls in VR. In addition, we also included a real-world, physical cockpit of a professional PFS as a baseline and "gold standard" in a fourth condition.

In a within-subjects study with 24 participants, we compared performance, task load, and simulator sickness during training of authentic cockpit manipulation tasks inside a VR replica of a Boeing 737-800NG cockpit for the three feedback methods. Additionally, we compared them to participants' interactions with the actual physical cockpit in a PFS. The participants were asked to train and execute typical aviation tasks by manipulating push buttons, rocker switches, and dial knobs, as these three control types represent about 90 percent of all cockpit elements of the Boeing 737-800NG. To achieve an in-depth analysis and understanding of the movements and interactions inside the VRFS and PFS, we recorded all hand and finger trajectories over time to differentiate the users' *movement time* (i.e., time to reach the target switch) from the *manipulation time* (i.e., time needed to set a switch to its target state).

The study revealed several findings about the advantages and disadvantages of using commercial, off-the-shelf VR technology to simulate safety-critical interactive spaces and the different methods for interacting with simulated controls in a VRFS:

(1) **Equivalence of VRFS and PFS:** There were no significant differences in error rates (and thus training success) between PFS and the three feedback methods in VRFS. There were also no significant differences between VRFS and the physical cockpit in terms of the Raw TLX subscales mental demand, physical demand, temporal demand, performance, and effort.
(2) **Control-specific differences:** There are no significant differences in *manipulation time* for push buttons and rocker switches in PFS and all VRFS conditions. It is, however, significantly higher for dial knobs. Problems with dial knobs in VR were also confirmed in semi-structured interviews and contribute to a significantly higher Raw TLX frustration subscale for VRFS than for PFS.
(3) **Irrelevance of vibrotactile feedback:** Compared to acoustic feedback, the inclusion of the off-the-shelf data glove for rudimentary vibrotactile feedback did not significantly affect the *manipulation time*.
(4) **Slower movements in VR:** The average and median *movement time* in *PFS* was significantly lower than in all VR conditions. Participants generally moved their hands more slowly in VR, contributing to slower task completion.
(5) **Preference for PFS and simulator sickness:** Despite comparable objective performances, most participants subjectively preferred PFS over VRFS. Simulator sickness contributed to this. After exposure, the mean score of the Simulator Sickness Questionnaire (SSQ) remained in the "minimal symptoms" category for PFS but moved into the "significant symptoms" category for VRFS. However, the increased SSQ results can be mostly attributed to just three of the 24 participants. They were the only ones reporting strong symptoms. These symptoms were in the oculomotor or disorientation category (but not in nausea), primarily stating blurred vision and eye strain as reasons.

We conclude that commercial, off-the-shelf VR technologies can be used for cost-effective simulations of safety-critical interactive spaces, even when they contain many physical controls. However, although roughly equivalent performance and error rates can be expected, better interaction designs are necessary to improve the manipulation of more complex controls in VR, e.g., simulated dial knobs. Simply adding the rudimentary vibrotactile feedback of a commercial data glove will most likely *not* result in relevant improvements. Also, since hand movements are generally slower in VR, greater *movement time* and slower task completion in VR have to be expected—even when problems of dial knob manipulation will be reduced in the future.

2 RELATED WORK

This work is positioned in the context of three areas of related work: Virtual Reality Flight Simulation, Input Methods in Virtual Reality Flight Simulators, and Haptic Feedback in Virtual Reality.

2.1 Virtual Reality Flight Simulation

Flight simulators help to reduce the complexity of flying, as they allow training under safe conditions. The origins of physical flight simulators can be traced back to early non-digital examples using adapted parts from sewing machines [39]. Since then, flight simulators have become an essential part of pilot training, as they enable realistic training of essential airmanship skills. Pilots train standard operation procedures (SOP), critical situations, and especially emergencies with great realism, but without putting the aircraft, the crew, or even passengers at risk.

Recent flight simulators often employ VR technology for more realistic training conditions and, thus, new ways of aviation pilot training [35, 41]. Such VRFS enable the training of pilots outside a physical cockpit but in a flexible, cost-effective, and sometimes photo-realistic interactive 3D space. Therefore, VR flight simulation is perhaps the most pervasive and successful part within VR simulation [40]. VRFS are used as professional training devices [44, 58], for testing flexible cockpit layouts [4, 59], or even for entertainment and gaming [50]. As low-cost alternatives to "full" VR, previous work also focused on basic cockpit training by learning check procedures from viewing 360° videos [36].

Airlines and flying schools are aware of the potential savings [12, 52] by VRFS, as they seek affordable and realistic substitutions for PFS for parts of the pilot training [26]. Also, the use of VR in pilot training has already been approved for certain parts[1] by the European Union Aviation Safety Agency (EASA)[2]. Previous work confirms the possible cost savings by using off-the-shelf hard- and software for cockpit familiarization training but also revealed problems with increased simulator sickness of VRFS compared to PFS [5].

VRFS have also been used as design tools. Previous work has compared the fidelity of a VRFS to a hardware cockpit mockup during flying tasks to evaluate the possible role of a VRFS in the early phases of the cockpit design process [32]. While some previous research has used simplified cockpit mockups [7, 24, 30, 45], our research uses a full-scale replica of an identical aircraft type for comparing PFS and VRFS, in order to provide a high level of internal validity.

2.2 Input Methods in Virtual Reality Flight Simulators

Current VR technologies require the user's physical interactions for manipulating simulated buttons, switches, displays, etc. to be technologically mediated. This can happen by using physical mockups [32], holding input devices (e.g. VR controllers [5]), using ultrasound [15], optical tracking [4, 57], or touch screens [21]. However, holding an input device limits the free movement of all fingers, and current input devices based on ultrasound, optical tracking, and touch screens provide limited flexibility, as they are constrained to a predefined position or a certain FOV of the provided sensor.

To avoid such trade-offs and also to provide haptic feedback, at least for selected controls, other researchers [27, 58] and commercial products[3] integrated physical joysticks and thrust levers into their VRFS. However, adding physical elements to a virtual cockpit makes the simulated cockpit less flexible toward the representation of different cockpit layouts.

[1]EASA approves the first Virtual Reality (VR) based Flight Simulation Training Device https://www.easa.europa.eu/en/newsroom-and-events/press-releases/easa-approves-first-virtual-reality-vr-based-flight-simulation
[2]European Union Aviation Safety Agency https://www.easa.europa.eu/
[3]*Adams Group* Multi-Task-Trainer https://adamsgroup.de/sit/

Using voice commands and speech recognition could overcome the mentioned trade-offs, but previous work of Rustamov et al. show an average of 89.6% correct recognition [42] in flight simulation, which is too low for safety-critical interactive spaces. Another approach for the interaction with virtual switches uses gaze-based interactions [49]. However, voice or gaze-based interaction does not make use of the pilot's muscle memory – one of five major attributes required for a safe flight [16].

2.3 Haptic Feedback in Virtual Reality

The lack of haptic or tactile feedback can have a negative effect on the user performance when interacting with virtual elements. For example, Aslandere et al. [4] used an optical system for finger tracking to generate a virtual hand within a virtual cockpit without haptic feedback, with which users achieved an average hit rate of only 77% . Novel input devices with haptic feedback can be used for enhanced user input in VR cockpits, such as the *Haptic Revolver* [54] or robotic arm-based systems like *Snake Charmer* [3], or even force feedback [1], but with limited movement space. However, the mentioned technologies are prototypes and are not easily available on the market yet (e.g., Dexmo Glove [17]).

Haptic feedback can also be generated using ultrasound [9, 13], actuators [14], or glove-based approaches with vibrators [48, 56]. Depending on their application area, vibrotactile devices are used on the wrist [53], arm [47], or on one [43] or even multiple fingertips [37, 43, 46]. None of the mentioned technologies were used in pilot training within a virtual cockpit representation of a commercial aircraft.

3 METHOD AND STUDY DESIGN

For our work, we compared a VRFS using different feedback modalities to a full-scale physical cockpit replica of a Boeing 737-800NG with all original instruments, which flight simulator enthusiasts built as part of a commercial attraction. As this PFS focuses on entertainment, it was not certified by the EASA. However, adding fully functional circuit breakers it would fulfill the requirements for a Flight and Navigation Procedures Trainer (FNPT) Level II simulator[4]. Therefore, it supports the development of fundamental skills of pilot training and can be considered fully capable of basic cockpit manipulation tasks. The PFS was compared to a basic VRFS based on a *HTC Vive Pro*[5] HMD. The VRFS used an identical virtual cockpit model[6] of the Boeing 737-800NG. It was integrated, animated, and developed using *Unity*[7] as the main software component. All hand and finger movements in the PFS and VRFS were tracked using a *Manus* data glove[8] to ensure a valid comparison.

The goal of our study was a quantitative comparison of both simulator technologies in terms of basic cockpit interaction, self-reported task load, and self-reported simulator sickness during the manipulation of certain basic cockpit switches (dial knobs, rocker switches, and push buttons) that are used during the flight deck preparation and supplementary procedures according to the operations manual of the Boeing 737-800NG[9]. At the end of the task, we performed a semi-structured interview that helped us to explain our quantitative results. As the chosen buttons, switches, and

[4]Specifications for Aeroplane Flight Simulation Training Devices: https://www.easa.europa.eu/sites/default/files/dfu/CS-FSTD(A)%E2%80%94Issue2.pdf
[5]HTC Vive https://www.vive.com/
[6]3D model of a Boeing 737-800NG Cockpit: https://www.turbosquid.com/de/3d-models/3d-boeing-737-cockpit/1106313
[7]Unity Technologies https://unity.com/, v2021.2.11f1
[8]Manus Meta https://www.manus-meta.com/
[9]Boeing provides the Operation Manual only directly to airlines but declassified versions can be found for reference online, e.g., at http://toulouse747.com/wp-content/uploads/2018/12/Boeing-B737-700-800-900-Operations-Manual.pdf

knobs (e.g., landing light, weather radar) are not directly related to the aircraft's controls, we kept the simulated aircraft motionless in order to prevent any distraction caused by the movement of the outside scenery.

All test conditions were presented consecutively but randomized with *Latin Square*, inside the full-scale replica cockpit of the Boeing 737-800NG, on the left cockpit seat (captains' seat), and were performed with the right hand only, on two predefined seat positions. These two seat positions allowed us to perform all tasks for one participant within a single session:

- For PFS, the seat was moved into a predefined *forward position*, from which all relevant physical switches were reachable. The participants wore tracked data gloves for tracking the right hand and fingers during the interaction with real-world physical switches.
- For VR, the seat was moved to a predefined *backward position* to increase the available physical space for freely moving the headworn HMD and tracked hands and to avoid unintentionally touching physical switches or consoles.

For each task, the home position was a tangible marker (see Fig. 2A and B) on the right armrest that ensured an identical starting point of all trajectories in any condition, even when wearing the vision-blocking HMD. This home position allowed for a valid comparison between PFS and VRFS, as it is fixed to the right armrest of the left pilot seat while the seat was moved into the *forward* and *backward* position. In order to achieve correct scales and distance measurements within the virtual cockpit, two VR base stations, and a VR tracker were set on predefined positions within the cockpit (see Fig. 2D).

3.1 Participants

We invited 24 study participants. To avoid biases for or against new simulator technologies due to previous training or experiences, none of them had an active pilot license, more than 10 hours of experience in a flight simulator, or more than 10 hours of VR experience.

The participants (19-45 years, M=33.71, SD=8.29, 12 female, 12 male) were split into two groups. One half of the participants started with the PFS, and the other half started with the VRFS. We ensured that the used data glove fitted tightly on the right hand so the fingertips were not covered by fabric.

This enabled unimpaired physical interactions with the physical switches in PFS, as the PFS was used as "golden standard" (see Fig. 2C). Three of the participants were left-handed (12.5%), 21 were right-handed (87.5%). This corresponds to recent estimates of a 10.6% ratio of left-handed persons [34]. The participants' vision was either normal or corrected to normal, using glasses or contact lenses that fitted underneath the HMD. The interpupillary distance (IPD) was measured using the provided method of the HMD's manufacturer.

3.2 Apparatus

3.2.1 Hardware Configuration of PFS. The PFS software was running on a PC with Windows 10 and an Intel i7 with 3.6 GHz, a Nvidia GeForce GTX 1080Ti GPU, and 32 GB RAM. The rendering of the external environment outside the cockpit (e.g., the runway) could be seen through the cockpit's windows and was projected with three HD projectors on a 180° cylindrical screen in front of the cockpit. However, our study contained no tasks that put the aircraft in motion and required viewing the external environment. Our PFS did not include a full-motion platform.

3.2.2 Hardware Configuration of VRFS. The VRFS used a laptop with Windows 10, an Intel i5 with 4.1 GHz CPU, a Nvidia GeForce RTX 2070 Super GPU, and 32 GB RAM. As HMD for the VRFS, we used a HTC Vive Pro with positional tracking (six degrees of freedom), providing a resolution of 1440x1600 pixel per eye, and integrated headphones. One advantage of the used HMD is the high

Fig. 2. Details of our study: (A) tangible marker at starting position on right armrest (red), (B) participant puts right index finger at starting position, (C) no fingertips were covered by the gloves to enable unimpaired physical interaction with real cockpit switches in PFS, (D) and (E) visual feedback when touching a control in VR. (F) and (G) slight mismatch between physical hand and hand representation in VR when touching the finger tips of the index finger and the thumb.

availability on the market, which (as mentioned in section 1) makes it interesting for flying schools to use them in classroom situations or even at home.

For the hand- and finger-tracking in VR, we chose to use *Manus Prime II Haptic* gloves[10]. We decided on the Manus gloves as they provide basic vibrotactile feedback on each finger without covering the fingertips with fabric. Also, compared to other finger tracking systems based on front-facing cameras or sensors, the trajectories of hand and fingers can be tracked outside the FOV of the optical sensor of the HMD, which is a significant advantage given the importance of also enabling eyes-free, haptic-only interaction with switches in cockpits.

To mimic a more natural interaction with PFS switches, we included different feedback modalities in the VRFS. In the first condition, participants were provided with visual and vibrotactile feedback during the interaction with the cockpit switches to provide stimuli on each finger while manipulating different cockpit elements. In a second condition, participants were provided visual and acoustic feedback whenever a virtual switch was manipulated. In a third condition, visual, vibrotactile, and acoustic feedback were provided simultaneously. Accordingly, visual feedback (i.e., visual highlighting of the touched control) was present in every condition (Fig. 2D and E).

3.2.3 Simulation Software Stack for PFS and VRFS. Our implementation of the VRFS aimed to create a high level of similarity between the VRFS and PFS to ensure high internal validity of the study. We provided the identical aircraft type, cockpit layou,t and switch positions in VRFS and PFS. Unity was the primary software component as it was used for the visual representation within the HMD, hand- and finger tracking, playing audio files, recording the switch positions, measurement of timing and distance, and logging.

[10]Manus Meta https://www.manus-meta.com/

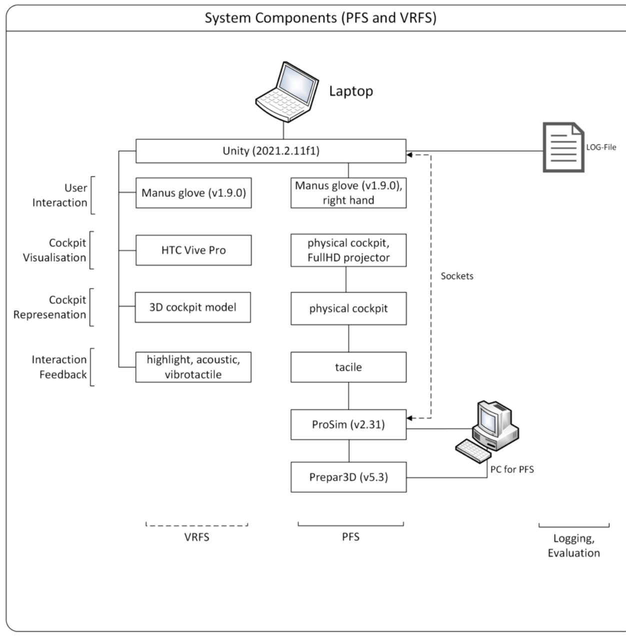

Fig. 3. The VRFS and PFS were based on Unity as the leading software component. Unity was used for visual representation in VR, recording, visualization of hand- and finger tracking, playing audio files, communication to the PFS via sockets, recording of switch positions, measurement of timing and distance, as well as logging.

The user interface in the VRFS was based on the Unity plugin and code examples provided by Manus. The interface between Unity and the PFS was built on network sockets connected to the ProSim[11] software of the PFS. The PFS itself was running on the commercial simulator software Prepar3D by Lockheed Martin[12] (Fig. 3). The VRFS was running at a minimum of 90 frames per second (FPS) during the test conditions, which is a recommended minimum for VR applications [2].

3.3 Independent Variables

To compare the differences between PFS and VRFS, we used the type of feedback methods for interacting with the cockpit's elements.

3.3.1 Feedback Methods. The type of feedback during the interaction with cockpit elements was either PFS or a consumer-grade stereoscopic, cost-efficient VRFS with three different feedback modalities, resulting in four different feedback modalities that we presented counterbalanced:

- PFS: real world, physical flight simulator feedback,
- VR_{aud}: acoustic feedback during the manipulation in VR
- VR_{hap}: vibrotactile feedback for rudimentary haptic support during the manipulation of cockpit elements and
- VR_{all}: combined acoustic and vibrotactile feedback.

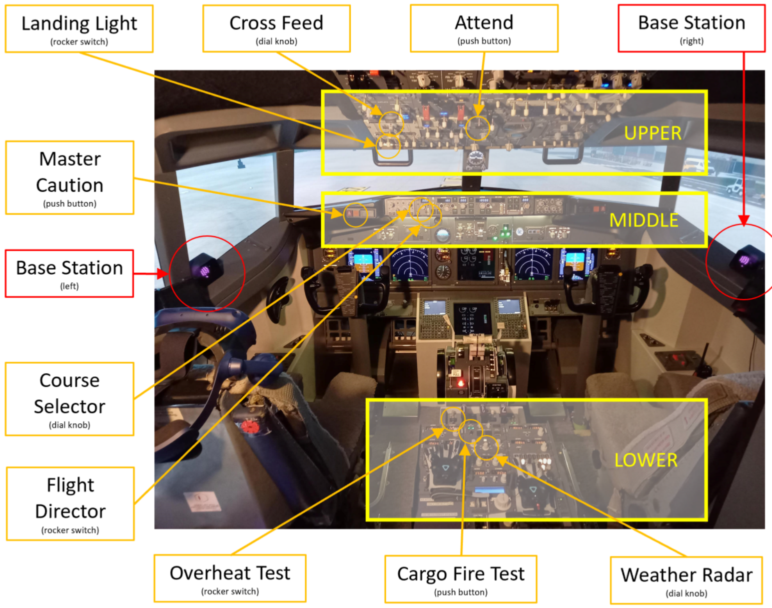

Fig. 4. Details about the relevant elements within the aircraft cockpit. Nine different cockpit elements categorized into three different types (push button, rocker switch, dial knob) and in three different areas (upper, middle, lower) were selected. Two VR base stations were used to triangulate and scale the virtual cockpit.

3.4 Tasks

The participants performed basic cockpit manipulation tasks based on check procedures from the operations manual of the Boeing 737-800NG[13]. These tasks represent short but realistic actions regarding the pilots' checklist that can be performed with a single cockpit element (e.g., turning on the landing light). Participants were seated on the left seat of the cockpit. They executed actions with their right hand, which can be performed using either the index finger (push buttons and rocker switches) or thumb and index finger (dial knobs).

After an initial training phase, which was supported by the experimenter (first author of this paper and a former military jet-fighter pilot with 18 years of experience in aviation, who also designed, executed, and evaluated this study), the participants heard randomized, recorded audio files that contained a voice command to manipulate a specific cockpit element.

The cockpit elements (see Fig. 4) were divided into three different types (*push buttons*, *rocker switches*, and *dial knobs*) and three different areas (*upper*[14], *middle*[15], *lower*[16]). This resulted in nine tasks, represented in a 3x3 matrix within the aircraft cockpit (see Table 1).

[11]ProSim737 by ProSim Aviation Research B.V., https://prosim-ar.com/prosim737/
[12]Prepar3D by Lockheed Martin, https://www.prepar3d.com/
[13]Boeing provides the Operation Manual only directly to airlines but declassified versions can be found for reference online, e.g., at http://toulouse747.com/wp-content/uploads/2018/12/Boeing-B737-700-800-900-Operations-Manual.pdf
[14]The *upper area* is related to the *Overhead Panel* that is situated about 80 cm above the start position.
[15]The *middle area* contains many important switches, that are required for the handling of the Auto Pilot, and is about 45 cm above the start position.
[16]The *lower area* is placed about 30 cm below the start position

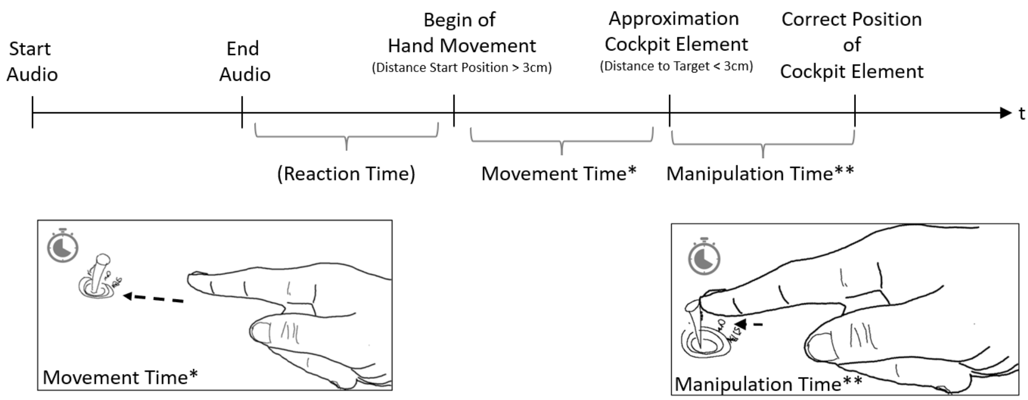

Fig. 5. The *movement time* describes the required time to move the virtual hand toward the target. The *manipulation time* contains the time required to move a specific cockpit element to the correct final position.

Table 1. Overview of the different cockpit manipulation tasks divided into the cockpit areas and element types. The presentation of the voice commands was randomized (*Latin Square*) and triggered by the experimenter.

	push button	*rocker switch*	*dial knob*
upper area	*"press Attend button."*	*"turn on Landing Light."*	*"rotate Crossfeed to the right."*
middle area	*"press Master Caution."*	*"turn on Flight Director."*	*"rotate Course Selector 10 degrees right."*
lower area	*"press Cargo Fire Test."*	*"turn on Overheat Test."*	*"rotate Weather Radar to test."*

3.5 Dependent Variables

For our study, we determined the following dependent variables.

3.5.1 Task Completion Time [sec]. The task completion time was measured while performing each cockpit manipulation task (see Fig. 5). It was split into two components. Firstly, the *movement time* which started with the initial hand movement and ended with entering a range of less than 3 cm to the relevant cockpit element. We determined a distance of 3 cm to provide space for the interaction and compensate for a slight mismatch in the finger tracking (as shown in Fig. 2F and G). Secondly, the *manipulation time* started at the end of the *movement time* and ended with reaching the desired final position of the cockpit element.

3.5.2 Error Rate [%]. The participants had to perform basic cockpit manipulation tasks. Two types of errors were recorded: first, an *incorrect switch error* occurred whenever an incorrect cockpit element was manipulated; second, a *switch position error* was detected whenever a switch was left in an incorrect position at the end of each task.

3.5.3 Perceived Workload. The participants' task load was measured using the NASA Task Load Index (NASA-TLX) [18] without paired comparisons of the subscales [8, 29], also known as *Raw TLX*. After performing all tasks in the PFS and all tasks in VR, the participants rated their *mental demand*, *physical demand*, *temporal demand*, *performance*, *effort*, and *frustration* on a scale ranging from *very low* (0) to *very high* (+10).

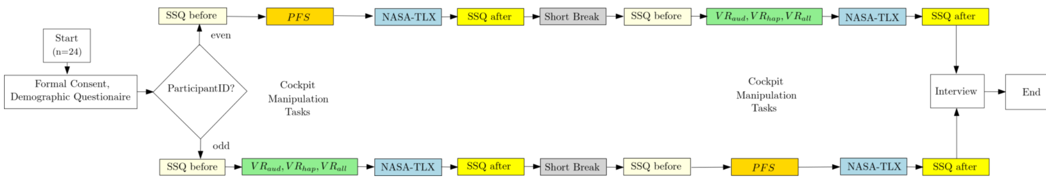

Fig. 6. Visualization of the within-subjects study procedure. In VR, the participants had to perform the cockpit manipulation tasks with all three feedback modalities (VR_{aud}, VR_{hap}, VR_{all}). The presentation of the cockpit manipulation tasks in VR was counterbalanced.

3.5.4 Simulator Sickness. The Simulator Sickness Questionnaire [23] was applied before and after each PFS and VRFS session. This standardized, subjective questionnaire measures 16 symptoms on a Likert-scale ranging from *not at all* (0) to *severe* (3). These symptoms are *general discomfort*, *fatigue*, *headache*, *eyestrain*, *difficulty focusing*, *increased salivation*, *sweating*, *nausea*, *difficulty concentrating*, *fullness of head*, *blurred vision*, *dizziness (eyes open)*, *dizziness (eyes closed)*, *vertigo*, *stomach awareness*, and *burping* which are assigned to the categories *nausea*, *oculomotor*, and *disorientation*. As some symptoms are associated with multiple categories, the categories are not disjunctive.

3.6 Procedure

Participants gave informed consent, filled out a demographic questionnaire, and a pre-exposure SSQ. The study strictly complied with all relevant guidelines and legal regulations concerning COVID-19.

Before each session, the data glove was calibrated with a standalone application provided by the manufacturer. Furthermore, the positions of all cockpit elements were recorded by touching the relevant object in the physical cockpit as well in VR. During an initial training phase supported by the experimenter, all participants could decide for themselves when they wanted to complete the learning phase and felt able to perform each task under test conditions. After performing all tasks, the participants filled out the NASA-TLX. Each test was concluded by filling out a post-exposure SSQ and, at the end of both sessions, answering the questions of the semi-structured interview. The interview gave participants the opportunity to informally share their experiences and comments. The following initial set of questions was used as a conversation starter:

- *Which simulator did you prefer? How many points do you assign to PFS and VRFS when you have in total 10 points available?*[17]
- *Can you tell us why have distributed the points in this way?*
- *Is there anything else you would like to share?*

On average, a complete test session took 10-15 minutes in the PFS and 15-20 minutes in the VRFS. A visual presentation of the study procedure is shown in Fig. 6.

4 RESULTS

This chapter contains detailed information about the results and the implications for future VRFS.

4.1 Movement Time

We expected similar *movement times* in the VRFS compared to the PFS, as the tasks, the distance between the starting point and target, and the scaling of the cockpit were identical. However, the average and median *movement time* in all VR conditions were slower (Fig. 7, Table 2) than the PFS.

[17]As the participants only had 10 points in total, a ranking with 7 to 3 was allowed, a ranking with 6 to 6 was not (6 + 6 >= 10 available points).

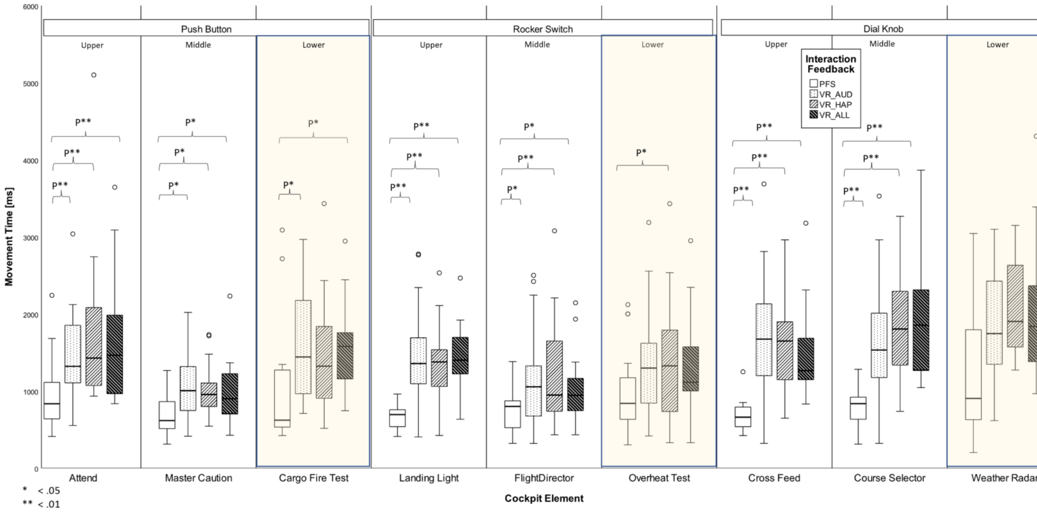

Fig. 7. Overview of *movement time*. We found statistically significant differences (Bonferroni corrected) between PFS and VRFS for *Attend*, *Master Caution*, *Cargo Fire Test*, *Landing Light*, *Flight Director*, *Overheat Test*, *Cross Feed*, and *Course Selector*. Cockpit elements in the lower area of the cockpit are highlighted with yellow, as the right armrest partly blocks the movement of these switches.

Looking at the data related to *Attend*, *Master Caution*, *Landing Light*, *Flight Director*, *Cross Feed*, and *Course Selector*, we found statistically significant differences between *PFS* and all three VR conditions VR_{aud}, VR_{hap}, and VR_{all}. These cockpit elements are situated in the *upper* or *middle area* of the aircraft cockpit and are, therefore, easy to reach.

Evaluating the remaining switches, we found statistically significant differences for *Cargo Fire Test* in the comparison of *PFS* with VR_{aud} and VR_{all}, and for *Overheat Test*, between *PFS* with VR_{hap}, but none for *Weather Radar*. The last three mentioned switches (highlighted with yellow in Fig. 7) are positioned in the *lower area*. They are more challenging to reach, as the right armrest blocks them and are outside the pilots' FOV whenever looking straight ahead in the cockpit. These buttons are either of low priority during the flight (e.g. test buttons), or are hardly used during a regular flight (e.g., fire extinguisher). As expected, we did not observe any significant difference between the VR conditions because the trajectories towards the cockpit elements are not affected by the interaction feedback, which happens later.

A possible explanation for the increased *movement time* in all VR conditions is depth underestimation [10], resulting in a reduced movement speed in the target's proximity. In order to get a better understanding of the underlying backgrounds, we performed a preliminary evaluation, which is described in detail in Chapter 6, as part of our outlook.

Result 1 - Movement Time: The average and median *movement time* in *PFS* is lower than in all VR conditions. This difference is statistically significant for all switches in the *upper* and *middle area* that are easy to reach and within the pilots' FOV whenever sitting in the left seat and looking straight ahead. The difference between PFS and VR is less significant for cockpit elements in the *lower area*, as they are blocked by the right armrest, resulting in a detoured trajectory both in the real world, and the virtual cockpit.

Table 2. This table shows the details regarding *movement time*, containing descriptive statistics, as well as information about the Friedman Test of the not normally distributed data, and the results of the Wilcoxon Signed Rank Tests with Bonferroni corrected p-values.

	Movement Time [ms]					p-values				Friedman Test		
		n	Mean	Median	SD	PFS	VR_aud	VR_{hap}	VR_{all}	$\chi^2(3)$	p	$W_{Kendall}$
Attend	PFS	24	1044.25	834.30	739.64	-	0.008**	<0.004**	<0.004**	22.481	<0.001**	0.312
	VR_aud	24	1433.50	1319.50	559.62	0.008**	-	0.796	0.944			
	VR_{hap}	24	1831.42	1427.70	1180.91	<0.004**	0.796	-	0.992			
	VR_{all}	24	1768.63	1464.50	1165.35	<0.004**	0.944	0.992	-			
Master Caution	PFS	24	739.04	616.50	506.51	-	0.024*	0.024*	0.036*	15.000	0.002**	0.208
	VR_aud	24	1252.04	1004.20	1188.78	0.024*	-	1.000	1.000			
	VR_{hap}	24	975.92	954.30	334.64	0.024*	1.000	-	1.000			
	VR_{all}	24	1098.45	899.50	784.81	0.036*	1.000	1.000	-			
Cargo Fire Test	PFS	24	1177.96	622.60	1301.38	-	0.012*	0.344	0.024*	18.693	<0.001**	0.260
	VR_aud	24	1749.88	1441.10	1185.97	0.012*	-	0.316	1.000			
	VR_{hap}	24	1396.88	1206.10	715.99	0.344	0.316	-	0.544			
	VR_{all}	24	1517.67	1579.50	548.06	0.024*	1.000	0.544	-			
Landing Light	PFS	24	730.88	694.90	292.63	-	<0.004**	<0.004**	<0.004**	27.050	<0.001**	0.376
	VR_aud	24	1433.67	1356.30	583.40	<0.004**	-	1.000	1.000			
	VR_{hap}	24	1332.46	1363.30	461.54	<0.004**	1.000	-	0.992			
	VR_{all}	24	1482.83	1400.40	603.37	<0.004**	1.000	0.992	-			
Flight Director	PFS	24	720.75	800.80	246.84	-	0.032*	0.008*	0.036*	12.113	0.007**	0.168
	VR_aud	24	1123.08	1054.00	606.04	0.032*	-	1.000	1.000			
	VR_{hap}	24	1216.08	947.50	670.27	0.008*	1.000	-	1.000			
	VR_{all}	24	986.92	944.40	421.82	0.036*	1.000	1.000	-			
Overheat Test	PFS	24	962.17	839.50	496.45	-	0.088	0.016*	0.168	11.130	0.011*	0.155
	VR_aud	24	1326.92	1297.20	661.29	0.088	-	1.000	1.000			
	VR_{hap}	24	1352.04	1326.30	761.18	0.016*	1.000	-	1.000			
	VR_{all}	24	1259.13	1112.50	596.49	0.168	1.000	1.000	-			
Cross Feed	PFS	24	716.96	660.60	292.52	-	<0.004**	<0.004**	<0.004**	36.416	<0.001**	0.506
	VR_aud	24	1731.38	1673.50	724.89	<0.004**	-	1.000	0.156			
	VR_{hap}	24	1540.92	1553.30	591.34	<0.004**	1.000	-	1.000			
	VR_{all}	24	1439.50	1263.20	493.27	<0.004**	0.156	1.000	-			
Course Selector	PFS	24	898.71	836.80	468.52	-	0.008**	<0.004**	<0.004**	29.008	<0.001**	0.403
	VR_aud	24	1648.58	1532.20	719.67	0.008**	-	0.608	0.092			
	VR_{hap}	24	1838.96	1804.80	689.74	<0.004**	0.608	-	1.000			
	VR_{all}	24	1961.79	1852.20	828.08	<0.004**	0.092	1.000	-			
Weather Radar	PFS	24	1544.67	903.30	2017.96	-	0.608	0.092	0.256	8.297	0.06	0.115
	VR_aud	24	2150.21	1744.70	1352.20	0.608	-	1.000	1.000			
	VR_{hap}	24	2002.29	1802.80	575.19	0.092	1.000	-	1.000			
	VR_{all}	24	1976.92	1837.80	825.50	0.256	1.000	1.000	-			

4.2 Manipulation Time

As our participants were rather inexperienced VR users, we expected increased *manipulation times* for the VR conditions. However, we found no statistically significant differences (see Fig. 3 and Table 3) for the push buttons *Attend*, *Master Caution*, and *Cargo Fire*. We found a single statistically significant difference for the rocker switches *Landing Light* between *PFS* and VR_{hap}, for *Flight Director* between *PFS* and VR_{aud}, and for *Overheat Test* between *PFS* and VR_{aud}.

Notably, there were statistically significant differences between *PFS* and all VR conditions dial knobs, where the median and mean *manipulation time* were consistently higher in VR. Participants also mentioned dial knobs in the interviews and that they are more difficult to manipulate in VR (P1, P2, P8, P12), and that VR is not as precise as PFS (P4, P7).

Interestingly, we did not observe any difference within the VR conditions VR_{aud}, VR_{hap}, and VR_{all}. In our study, the low-cost acoustic feedback was as effective as rudimentary vibrotactile feedback when manipulating virtual cockpit elements. Furthermore, for *Landing Light*, *Flight Director*, and *Overheat Test* the average and median *manipulation time* in PFS are higher than in the VR conditions. A possible explanation is that the physical switches are spring-loaded and need considerable force to be moved. This was not simulated in the VRFS.

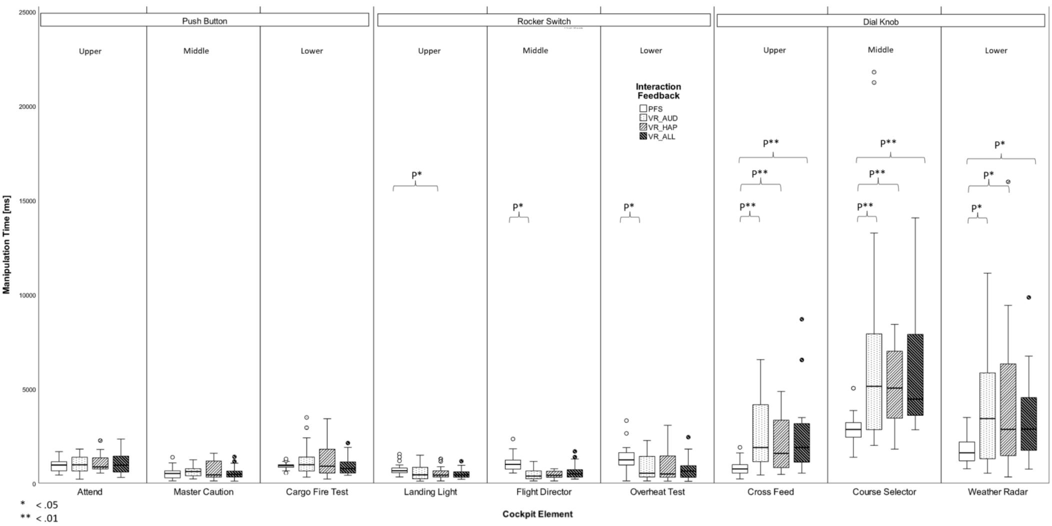

Fig. 8. Evaluation of *manipulation time*. We found statistically significant differences for *Landing Light* between PFS and VR_{hap}, for *Flight Director* between PFS and VR_{aud}, and for *Overheat Test* between PFS and VR_{aud}. Furthermore, we observed statistically significant differences for all dial knobs between PFS and all VR conditions.

Result 2 - Manipulation Time: The manipulation time of push buttons and rocker switches is quite similar in PFS and in VR. However, the most significant difference between the real world and the virtual cockpit is with dial knobs. Interestingly, we did not observe any difference within the VR conditions VR_{aud}, VR_{hap}, and VR_{all}. In addition, the rudimentary vibrotactile feedback did not have a significant positive influence on the manipulation time.

4.3 Error Rate

We did not observe any switch position error, neither in PFS, nor in the VR conditions. Furthermore, the number of incorrect switch errors was low among all conditions. The details about mean, median, standard deviation, and the results of the non-parametric Friedman Test for the not normally distributed data, can be found in Table 4. None of the comparisons were statistically significant. This result shows that the participants were able to select and interact correctly with the cockpit elements in all test conditions (PFS and VRFS).

Result 3 - Error Rate: Participants successfully performed basic cockpit manipulation tasks in VR without any switch position error and significant differences in incorrect switch error rates. Overall, there were no statistically significant differences in error rates between PFS, VR_{aud}, VR_{hap}, and VR_{all}.

4.4 Perceived Workload

Raw TLX was used for measuring task load during the user study (see Fig. 9). The data was not normally distributed and we applied a non-parametric test, accordingly. Looking at pairwise comparisons (Wilcoxon-Signed-Rank), we saw that only for the sub-scale *frustration* the differences between PFS and VR ($p < 0.001$) were statistically significant but not for the sub-scales *mental*

Table 3. This table shows the details regarding *manipulation time*, containing descriptive statistics as well as information about the Friedman Test of the not normally distributed data, and the results of the Wilcoxon Signed Rank Tests with Bonferroni corrected p-values.

	Manipulation Time [ms]					p-values				Friedman Test		
		n	Mean	Median	SD	PFS	VR_{aud}	VR_{hap}	VR_{all}	$\chi^2(3)$	p	$W_{Kendall}$
Attend	PFS	24	1034.83	955.50	645.14	-	1.000	1.000	1.000	2.121	0.548	0.029
	VR_{aud}	24	997.46	966.50	424.58	1.000	-	1.000	1.000			
	VR_{hap}	24	1019.21	847.40	421.07	1.000	1.000	-	1.000			
	VR_{all}	24	1245.88	947.40	1081.73	1.000	1.000	1.000	-			
Master Caution	PFS	24	526.58	506.50	293.41	-	1.000	1.000	1.000	1.468	0.690	0.020
	VR_{aud}	24	600.81	579.70	292.37	1.000	-	1.000	1.000			
	VR_{hap}	24	645.54	427.90	452.19	1.000	1.000	-	1.000			
	VR_{all}	24	529.17	461.60	331.21	1.000	1.000	1.000	-			
Cargo Fire Test	PFS	24	900.71	922.20	289.42	-	0.028*	0.256	0.092	0.540	0.910	0.007
	VR_{aud}	24	1163.13	973.70	796.01	0.028*	-	1.000	1.000			
	VR_{hap}	24	1109.42	797.90	793.37	0.256	1.000	-	1.000			
	VR_{all}	24	911.21	765.60	475.82	0.092	1.000	1.000	-			
Landing Light	PFS	24	712.92	652.50	305.93	-	0.368	0.028*	0.060	9.962	0.019*	0.138
	VR_{aud}	24	564.38	433.50	410.66	0.368	-	1.000	1.000			
	VR_{hap}	24	486.46	414.00	282.95	0.028*	1.000	-	1.000			
	VR_{all}	24	499.21	429.20	317.95	0.060	1.000	1.000	-			
Flight Director	PFS	24	1036.83	987.70	407.62	-	0.028*	0.268	0.076	16.908	<0.001**	0.235
	VR_{aud}	24	668.88	368.60	863.64	0.028*	-	1.000	1.000			
	VR_{hap}	24	815.88	413.50	979.76	0.268	1.000	-	1.000			
	VR_{all}	24	761.50	483.80	939.15	0.076	1.000	1.000	-			
Overheat Test	PFS	24	1485.92	1227.20	918.92	-	0.028*	0.256	0.092	10.941	0.012*	0.152
	VR_{aud}	24	1428.92	521.50	2594.91	0.028*	-	1.000	1.000			
	VR_{hap}	24	1198.75	560.60	1423.08	0.256	1.000	-				
	VR_{all}	24	840.88	632.30	854.54	0.092	1.000	1.000	-			
Cross Feed	PFS	24	826.25	748.00	412.31	-	<0.001**	<0.001**	<0.001**	27.377	<0.001**	0.380
	VR_{aud}	24	3163.79	1882.80	3759.18	<0.001**	-	0.836	1.000			
	VR_{hap}	24	2622.46	1572.70	3679.57	<0.001**	0.836	-	1.000			
	VR_{all}	24	2553.08	1884.50	2037.32	<0.001**	1.000	1.000	-			
Course Selector	PFS	24	2894.13	2838.50	895.76	-	<0.001**	<0.001**	<0.001**	14.096	0.003**	0.196
	VR_{aud}	24	6596.63	5124.40	5534.32	<0.001**	-	1.000	1.000			
	VR_{hap}	24	6076.71	4817.80	4788.95	<0.001**		-	1.000			
	VR_{all}	24	7559.75	4449.20	6655.36	<0.001**	1.000	1.000	-			
Weather Radar	PFS	24	1449.38	1428.50	460.64	-	0.048*	0.032*	0.048*	9.151	0.027*	0.127
	VR_{aud}	24	3821.67	3417.40	2805.15	0.048*	-	1.000	1.000			
	VR_{hap}	24	3988.58	2786.00	3653.76	0.032*	1.000	-	1.000			
	VR_{all}	24	4168.96	2856.60	4140.94	0.048*	1.000	1.000	-			

demand ($p = 0.055$), *physical demand* ($p = 0.063$), *temporal demand* ($p = 0.718$), *performance* ($p = 0.102$), and *effort* ($p = 0.096$).

We believe that the inaccuracy of the Manus data glove, in combination with the problematic manipulation of dial knobs led to an increased frustration among the participants, as e.g., P3 stated that he was *"disappointed whenever I had to manipulate a dial knob in VR"*. However, the overall feedback towards the VRFS was quite positive, as different participants stated that they had fun in VR (P13, P14, P15, P20, P24) and that they see great potential in VR for the future pilot training (P3, P24).

Result 4 - Workload: We did not observe statistically significant differences within the Raw TLX-values, except for the sub-scale *frustration*, which was mainly caused by problematic interaction with dial knobs.

4.5 SSQ and User Ranking

The SSQ questionnaire [22] was filled out before and after *PFS* session and *VRFS* session, so four times for each participant. According to SSQ literature, a total SSQ score between 5-10 is associated

Table 4. Evaluation of the low number of *Incorrect Switch Errors* including mean, median, and standard deviation. We did not perform post-hoc pairwise comparisons, as the Friedman Test did not indicate any significance.

		Error Rate				Friedman Test		
		n	Mean	Median	SD	$\chi^2(3)$	p	$W_{Kendall}$
Attend	PFS	24	0.00	0	0.00	3.000	0.392	0.043
	VR_{aud}	24	0.00	0	0.00			
	VR_{hap}	24	0.00	0	0.00			
	VR_{all}	24	0.04	0	0.20			
Master Caution	PFS	24	0.04	0	0.20	1.000	0.801	0.014
	VR_{aud}	24	0.04	0	0.20			
	VR_{hap}	24	0.00	0	0.00			
	VR_{all}	24	0.04	0	0.20			
Cargo Fire Test	PFS	24	0.00	0	0.00	2.000	0.572	0.028
	VR_{aud}	24	0.04	0	0.20			
	VR_{hap}	24	0.04	0	0.20			
	VR_{all}	24	0.00	0	0.00			
Landing Light	PFS	24	0.04	0	0.20	3.000	0.392	0.042
	VR_{aud}	24	0.00	0	0.00			
	VR_{hap}	24	0.00	0	0.00			
	VR_{all}	24	0.00	0	0.00			
Flight Director	PFS	24	0.08	0	0.28	2.538	0.468	0.035
	VR_{aud}	24	0.08	0	0.28			
	VR_{hap}	24	0.04	0	0.20			
	VR_{all}	24	0.00	0	0.00			
Overheat Test	PFS	24	0.08	0	0.28	6.000	0.112	0.083
	VR_{aud}	24	0.00	0	0.00			
	VR_{hap}	24	0.00	0	0.00			
	VR_{all}	24	0.00	0	0.00			
Cross Feed	PFS	24	0.00	0	0.00	4.714	0.194	0.065
	VR_{aud}	24	0.04	0	0.20			
	VR_{hap}	24	0.08	0	0.28			
	VR_{all}	24	0.00	0	0.00			
Course Selector	PFS	24	0.00	0	0.00	3.000	0.392	0.042
	VR_{aud}	24	0.00	0	0.00			
	VR_{hap}	24	0.00	0	0.00			
	VR_{all}	24	0.04	0	0.20			
Weather Radar	PFS	24	0.00	0	0.00	6.000	0.112	0.083
	VR_{aud}	24	0.00	0	0.00			
	VR_{hap}	24	0.00	0	0.00			
	VR_{all}	24	0.13	0	0.44			

with "minimal symptoms", 10-15 with "significant symptoms", 15-20 with "symptoms are a concern", and values above 20 with a "problem simulator"

Looking at the descriptive statistics, the total SSQ score after exposure describes the PFS as simulator with "minimal symptoms" ($Med = 3.74, Mean = 6.39, SD = 7.02$) and the $VRFS$ as simulator with "significant symptoms", yet very close to the lower boundary ($Med = 4.71, Mean = 10.21, SD = 11.58$).

In order to understand the influence of PFS and $VRFS$ on the participants, we calculated the difference between the pre- and post-exposure. By applying Wilcoxon-Signed-Rank test for the pairwise comparisons and as shown in Fig. 10, we did not find any significance in the SSQ-Difference in any of the four SSQ-Categories *nausea* ($p = 0.632$), *oculomotor* ($p = 0.712$), *disorientation* ($p = 0.336$), and *total score* ($p = 0.962$). This result shows a slightly higher *SSQ-Total Score* for the VRFS (mainly caused by P3, P6, and P18) but no significantly increased simulator sickness for VR.

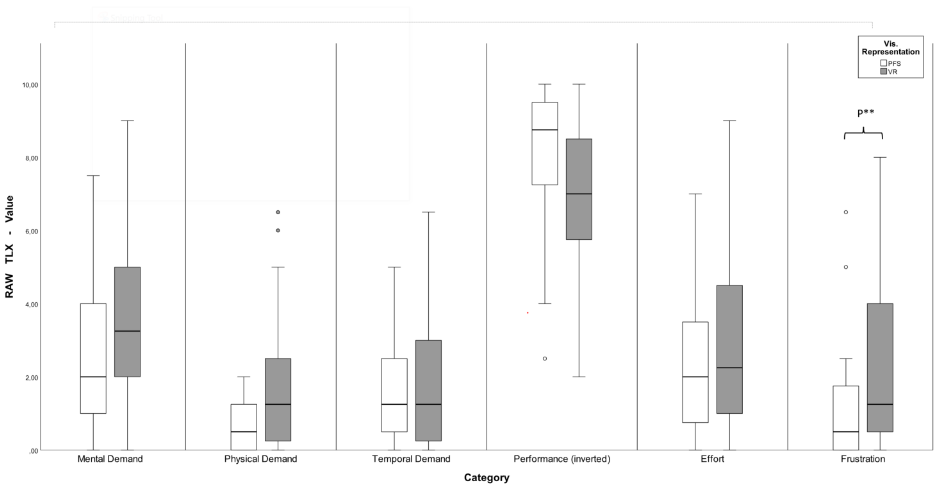

Fig. 9. The analysis of the Raw TLX values indicates statistically significant differences only for the subscale *frustration*.

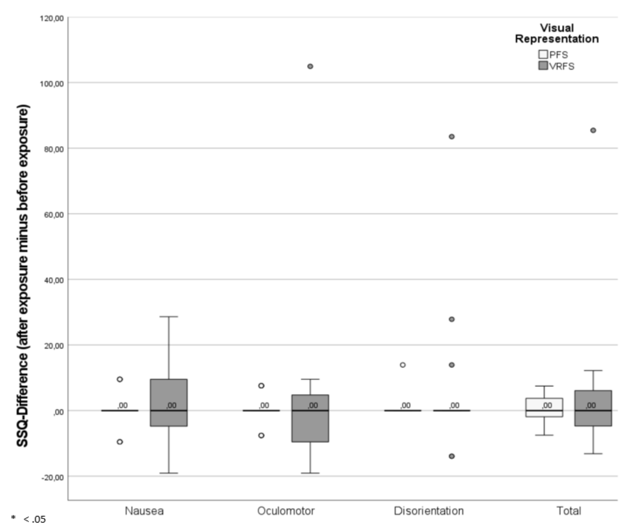

Fig. 10. Box plot of the perceived change in Simulator Sickness due to the exposure to either PFS or VRFS. The change was not statistically significant for all SSQ dimensions.

Looking at the evaluation of the distribution of the user-reported scoring, the majority of the participants preferred PFS over VRFS (see Fig. 11). This difference was statistically significant ($p < 0.001$). Interestingly, three of the 24 participants favored virtual reality over the physical cockpit. In addition, the semi-structured interview revealed positive feedback towards the used VRFS. Some stated that the virtual cockpit is already close to the real cockpit (P18,P19,P22,P23), and that they can imagine using VRFS as a training device during pilot training (P3, P12,P21,P23).

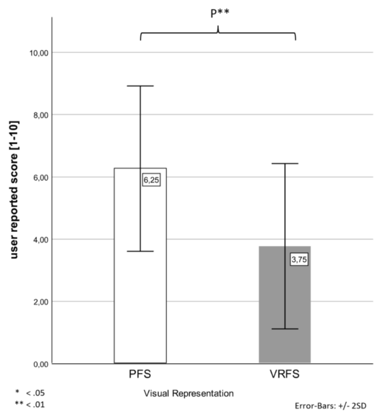

Fig. 11. Self reported distribution of max. 10 points, that were assigned either to PFS or VRFS, as response to *Which simulator did you prefer?*

Result 5 - Simulator Sickness: The participants reported SSQ related "minimal symptoms" for PFS and "significant symptoms" VRFS. The increased SSQ results can be mostly attributed to three of the 24 participants who reported strong symptoms in the Oculomotor or Disorientation category but not for Nausea, primarily stating blurred vision and eye strain as reasons.

5 DISCUSSION

In our study, we compared different interaction types inside a commercial aircraft cockpit of a Boeing 737-800NG with push buttons, rocker switchers, and dial knobs in VR using different feedback methods such as visual, auditory and/or haptic feedback. With our work, we intend to find out if we can employ current commercial, off-the-shelf VR technologies for a cost-effective simulation of interactive spaces containing many physical controls while minimizing the previously reported adverse effects. Our main results indicate the advantages but also shortcomings, which are discussed in this chapter.

5.1 Equivalence of VRFS and PFS

We did not observe significant differences in error rates (no recorded *switch position errors* and low rate of *incorrect switch errors*) between the three VR feedback methods (VR_{aud}, VR_{hap}, and VR_{all}) and PFS (Table 4). This is a clear indicator for the training success of the VR cockpit representation, as the buildup of *muscle memory* - one of five major attributes required for a safe flight [16] - is supported. Furthermore, there were no statistically significant differences between VRFS and the physical cockpit concerning the Raw TLX sub-scales *mental demand*, *physical demand*, *temporal demand*, *performance*, and *effort* (Fig. 10), that emphasizes the high level of equivalence between VRFS and PFS.

5.2 Control-Specific Differences

Our results do not indicate significant differences in *manipulation time* for push buttons and rocker switches in PFS and all VRFS conditions (Fig. 8, Table 3). However, the the Raw TLX sub-scale for *frustration* (Fig. 10) shows a statistically significant difference between PFS and VRFS, mainly caused by the problematic interaction with dial knobs. These differences are confirmed by the participants' comments in the semi-structured interview, declaring the interaction with dial knobs as main shortcoming of the presented VRFS. The used data glove did not cover the fingertips of the participants providing an uninfluenced interaction with the cockpit elements, even in the physical environment, representing the "golden standard".

5.3 Irrelevance of Vibrotactile Feedback

The rudimentary vibrotactile feedback provided by the data glove did not significantly influence the *manipulation time* compared to the visual and acoustic feedback (Fig. 8, Table 3). We are convinced that the cheaper acoustic feedback is sufficient for the basic aircraft cockpit manipulation tasks and that the used vibrotactile does not provide an increased training result. More complex technologies based on, e.g., ultrasound [15] or force-feedback [17] might provide more suitable support in the future.

5.4 Slower Movements in VR

To our surprise, the participants generally moved their hands more slowly towards the VR cockpit elements, as average and median *movement time* in *PFS* was significantly lower than in all VR conditions (Fig. 7, Table 2). A possible explanation for the slower *movement time* might be the low experience of the participants using data-gloves. In order to reveal the underlying reasons for the increased *movement time*, we performed a deeper analysis of the recorded data introduced in Chapter 6 (Limitations and Outlook).

5.5 Preference for PFS and Simulator Sickness

Most participants subjectively preferred PFS over VRFS (Fig. 11) as a result of the semi-structured interview. After exposure, the mean score of the SSQ remained in the "minimal symptoms" category for PFS but moved into the "significant symptoms" category for VRFS. Still, the increased SSQ results are mainly attributed to three of the 24 participants who were the only ones reporting strong symptoms. These were in the oculomotor or disorientation category (but not in nausea), primarily stating blurred vision and eye strain as reasons.

5.6 Implications for VRFS Research and Practice

We conclude that commercial, off-the-shelf VR technologies can be used for cost-effective simulations of safety-critical interactive spaces, even when they contain many physical controls. Furthermore, the absence of physical switches did not impair participants' task completion and correctness. However, although roughly equivalent performance and error rates can be expected, better interaction designs are necessary to improve the manipulation of more complex controls in VR, e.g., simulated dial knobs. Simply adding the rudimentary vibrotactile feedback of a commercial data glove will most likely *not* result in relevant improvements. Also, since hand movements are generally slower in VR, increased *movement time* and slower task completion in VR have to be expected—even when problems of dial knob manipulation will be reduced in the future.

We are convinced that our results can be extended to other safety-critical interactive and virtual spaces, such as railway [33] and car simulators [11, 28], as the investigated interaction types and feedback methods are not limited to a commercial airplane cockpit. We admit that future complementary VR-based training has to focus on solving the problematic interaction with dial knobs because the resulting frustration negatively influences the learning outcome. Our study emphasizes the huge potential of VR as a complementary practice device within conventional training, even beyond aviation-related basic aircraft cockpit manipulation tasks. One indisputable advantage of using VR, within a training environment is the support of muscle memory that can be transferred directly to the real world environment [16].

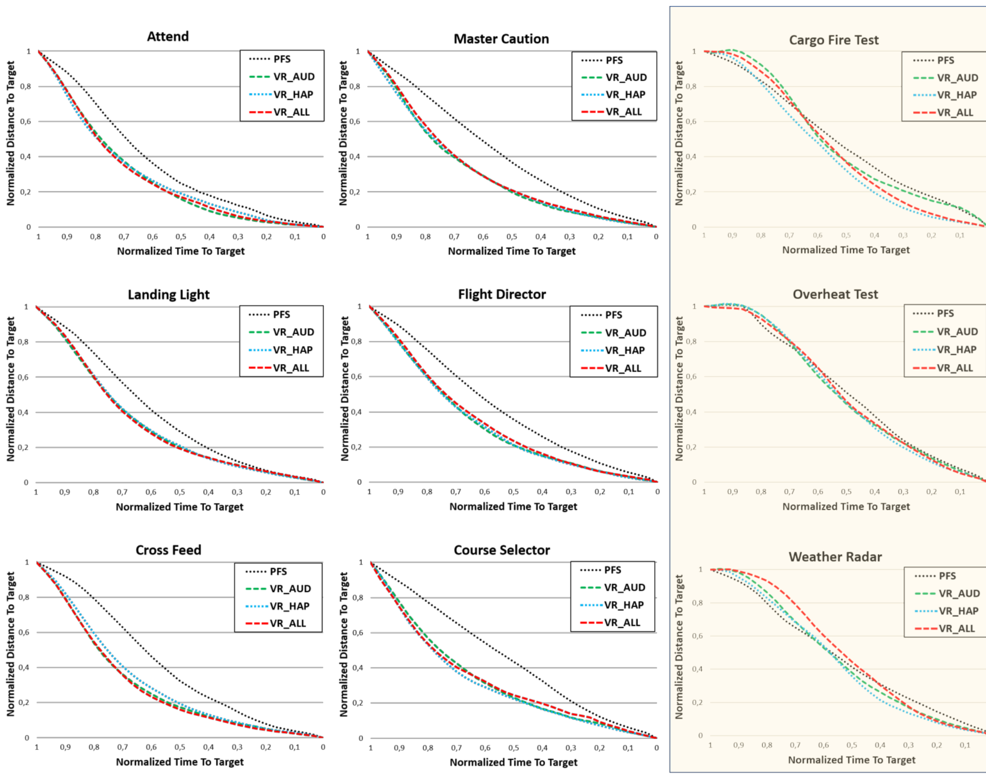

Fig. 12. Preliminary analysis of movement time that shows the average trajectory of the particpants during their movement towards the cockpit element. The x-axis of this chart describes the remaining time to the particular target within the normalized scale [1;0]. The y-axis represents the remaining distance towards the target within a the normalized scale of [1;0]. The average trajectory in PFS is a rather straight line between the points (1,1) and (0,0), that indicates a straight trajectory towards the target with a constant speed. The average trajectory in VR shows a decreased speed in the proximity of the target. As the cockpit elements in the *lower Area* are partly blocked by the right armrest, the participants were forced to move their hand radially, before they were able to proceed to the final point.

6 LIMITATIONS AND OUTLOOK

In our study, we had to deal with different limitations. First, as shown in Fig. 2F and G, the used data gloves provide a high but not fully precise representation of the physical hand in VR. Upcoming data gloves might provide higher precision and, therefore, more realistic finger tracking that can positively affect the interaction, especially with dial knobs.

Second, in many cases the participants performed the tasks only once in every test condition. We did not evaluate the influence of repetitive tasks and the resulting learning effect on *movement time* and *manipulation time*, especially in the virtual environment.

The analysis of the *movement time* in Chapter 4.1 indicates a significant difference between *PFS* and all VRFS conditions. In order to get a better understanding of the increased movement time in VR, we plotted a chart (see Fig. 12) of the average hand trajectory of all 24 participants. The x-axis of this chart describes the remaining time to the particular target within the normalized scale [1;0], where 1 represents the beginning, and 0 the end of observed movement time. The y-axis represents the remaining distance towards the target within the normalized scale of [1;0], where 1 marks the beginning, and 0 the end of observed movement time. In this chart, a fictitious straight line between the points (1,1) and (0,0) indicates a straight trajectory towards the target with a constant speed.

Interestingly, the average trajectories in PFS are closer to this fictitious straight line compared to the trajectories in VRFS. A trajectory below this fictitious straight line describes a hand trajectory with a reduced speed at the end of the movement, which is the case for the cockpit elements in the *upper* and *middle* cockpit area. Above it, it indicates a reduced speed at the beginning of the trajectory, which can be observed at the cockpit elements in the *lower* cockpit area.

In a preliminary analysis, which can be extended in the future, we found out that the movements in our *PFS* conditions were performed quite straight towards the target with a constant speed for all cockpit elements. The trajectories in VR (VR_{aud},VR_{hap}, and VR_{all}) show a reduced speed at the end of the movement time, resulting in statistically significant differences for the tasks *Attend*, *Landing Light*, *Cross Feed*, *Master Caution*, *Flight Director*, and *Course Selector*, situated in the *upper* and *Middle* cockpit area. Our observed results of the trajectories coincide with previous research [6], reporting sigmoid-shaped trajectories during aimed mid-air movements in VR. A possible explanation for the increased movement time can be found in previous work, reporting depth underestimation in VR [38], which results in a decreased speed near the target.

7 CONCLUSION

We presented the results of a user study that compared a full-scale physical flight simulator of a Boeing 737-800NG with a cost-efficient virtual reality flight simulator for basic cockpit manipulation tasks with a data glove with vibrotactile and acoustic feedback. Based on our findings, the similar manipulation times for push buttons and rocker switches, low error rates, moderate SSQ values, and similar NASA-TLX values show the potential for VR to be used as a safety-critical interactive space. However, the increased movement times and the significantly higher manipulation times of dial knobs led to a significantly increased frustration among the participants, indicating the potential for further development.

ACKNOWLEDGMENTS

This publication is a part of the X-PRO project. The project X-PRO is financed by research subsidies granted by the government of Upper Austria. We also want to thank *Adams Simulation and Training*[18] for providing VR hardware and Synthetic737[19] for the support during the user study.

REFERENCES

[1] Andrea F. Abate, Mariano Guida, Paolo Leoncini, Michele Nappi, and Stefano Ricciardi. 2009. A haptic-based approach to virtual training for aerospace industry. *Journal of Visual Languages & Computing* 20, 5 (2009), 318–325. https://doi.org/10.1016/j.jvlc.2009.07.003

[2] Gae Ae Ryu and Kwan-Hee Yoo. 2020. Key Factors for Reducing Motion Sickness in 360° Virtual Reality Scene: Extended Abstract. In *The 25th International Conference on 3D Web Technology* (Virtual Event, Republic of Korea) *(Web3D '20)*. Association for Computing Machinery, New York, NY, USA, Article 28, 2 pages. https://doi.org/10.1145/3424616.3424723

[3] Bruno Araujo, Ricardo Jota, Varun Perumal, Jia Xian Yao, Karan Singh, and Daniel Wigdor. 2016. Snake Charmer. In *TEI '16*, Saskia Bakker, Caroline Hummels, and Brygg Ullmer (Eds.). ACM, New York, 218–226. https://doi.org/10.1145/2839462.2839484

[4] Turgay Aslandere, Daniel Dreyer, Frieder Pantkratz, and Rene Schubotz. 2014. A generic virtual reality flight simulator. In *Virtuelle und Erweiterte Realität, 11. Workshop der GI-Fachgruppe VR/AR*. Shaker Verlag, Bremen, Germany, 1–13.

[5] Stefan Auer, Jens Gerken, Harald Reiterer, and Hans-Christian Jetter. 2021. Comparison Between Virtual Reality and Physical Flight Simulators for Cockpit Familiarization. In *Mensch Und Computer 2021* (Ingolstadt, Germany) *(MuC '21)*. Association for Computing Machinery, New York, NY, USA, 378–392. https://doi.org/10.1145/3473856.3473860

[18] Adams Simulation and Training https://adamssimulationandtraining.de/

[19] Synthetic737 https://www.synthetic737.at

[6] Myroslav Bachynskyi and Jörg Müller. 04212020. Dynamics of Aimed Mid-air Movements. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, Regina Bernhaupt, Florian 'Floyd' Mueller, David Verweij, Josh Andres, Joanna McGrenere, Andy Cockburn, Ignacio Avellino, Alix Goguey, Pernille Bjørn, Shengdong Zhao, Briane Paul Samson, and Rafal Kocielnik (Eds.). ACM, New York, NY, USA, 1–12. https://doi.org/10.1145/3313831.3376194

[7] Pradipta Biswas and Jeevithashree DV. 2018. Eye Gaze Controlled MFD for Military Aviation. In *23rd International Conference on Intelligent User Interfaces (IUI '18)*. ACM, New York, NY, USA, 79–89. https://doi.org/10.1145/3172944.3172973

[8] James C Byers. 1989. Traditional and raw task load index (TLX) correlations: Are paired comparisons necessary? *Advances in Industrial Ergonomics and Safety l: Taylor and Francis.* 1, 1 (1989), 481–485.

[9] Tom Carter, Sue Ann Seah, Benjamin Long, Bruce Drinkwater, and Sriram Subramanian. 2013. UltraHaptics: multi-point mid-air haptic feedback for touch surfaces. In *Proceedings of the 26th annual ACM symposium on User interface software and technology - UIST '13*. ACM Press, St. Andrews, Scotland, United Kingdom, 505–514. https://doi.org/10.1145/2501988.2502018

[10] Sarah Creem-Regehr, K. Myszkowski, Bobby Bodenheimer, Betty J. Mohler, Bernhard Riecke, and Stephen N. Spencer. 2008. *Proceedings APGV 2008: Symposium on Applied Perception in Graphics and Visualization Los Angeles, California, August 9-10, 2008.* ACM Press, New York.

[11] Daniele Sportillo, Alexis Paljic, and Luciano Ojeda. 2019. *HRI'19: The 14th ACM/IEEE International Conference on Human-Robot Interaction : March 11-14, 2019, Daegu, South Korea.* IEEE, Piscataway, NJ.

[12] Kai-Uwe Doer, Jens Schiefel, and W. Kubbat. 2001. *Virtual Cockpit Simulation for Pilot Training*. Technical Report. University of Darmstadt (Germany).

[13] Tafadzwa Joseph Dube, Yuan Ren, Hannah Limerick, I. Scott MacKenzie, and Ahmed Sabbir Arif. 2022. Push, Tap, Dwell, and Pinch: Evaluation of Four Mid-air Selection Methods Augmented with Ultrasonic Haptic Feedback. *Proceedings of the ACM on Human-Computer Interaction* 6, ISS (2022), 207–225. https://doi.org/10.1145/3567718

[14] Joseph Dumas, Andrew Novobilski, Dawn Ellis, and Mark Paschal. 2002. VR on a Budget: Developing a Flight Simulator in a Small Institution with off-the-Shelf Hardware and Open Source Software. *J. Comput. Sci. Coll.* 18, 2 (Dec. 2002), 138–142.

[15] Alex Girdler and Orestis Georgiou. 2020. Mid-Air Haptics in Aviation–creating the sensation of touch where there is nothing but thin air. *ArXiv* abs/2001.01445 (2020).

[16] Jerome N. Gregoire, Celeste M. Alfes, Andrew P. Reimer, and Mary F. Terhaar. 2017. Flying Lessons for Clinicians: Developing System 2 Practice. *Air Medical Journal* 36, 3 (May 2017), 135–137. https://doi.org/10.1016/j.amj.2017.02.003

[17] Xiaochi Gu, Yifei Zhang, Weize Sun, Yuanzhe Bian, Dao Zhou, and Per Ola Kristensson. 05072016. Dexmo. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, Jofish Kaye, Allison Druin, Cliff Lampe, Dan Morris, and Juan Pablo Hourcade (Eds.). ACM, New York, NY, USA, 1991–1995. https://doi.org/10.1145/2858036.2858487

[18] Sandra G. Hart and Lowell E. Staveland. 1988. Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research. In *Advances in Psychology*. Vol. 52. Elsevier, Amsterdam, 139–183. https://doi.org/10.1016/S0166-4115(08)62386-9

[19] Hans-Christian Jetter, Roman Rädle, Tiare Feuchtner, Christoph Anthes, Judith Friedl, and Clemens Nylandsted Klokmose. 2020. "In VR, Everything is Possible!": Sketching and Simulating Spatially-Aware Interactive Spaces in Virtual Reality. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–16. https://doi.org/10.1145/3313831.3376652

[20] Hans-Christian Jetter, Harald Reiterer, and Florian Geyer. 2014. Blended Interaction: Understanding Natural Human—Computer Interaction in Post-WIMP Interactive Spaces. *Personal Ubiquitous Comput.* 18, 5 (jun 2014), 1139–1158. https://doi.org/10.1007/s00779-013-0725-4

[21] Richard Joyce and Stephen K. Robinson. 2019. Evaluation of a Virtual Reality Environment for Cockpit Design. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 63, 1 (2019), 2328–2332. https://doi.org/10.1177/1071181319631309

[22] Robert S Kennedy, Julie M Drexler, Daniel E Compton, Kay M Stanney, D Susan Lanham, and Deborah L Harm. 2003. Configural Scoring of Simulator Sickness, Cybersickness and Space Adaptation Syndrome. In *Virtual and adaptive environments*, Lawrence J. Hettinger and Michael W. Haas (Eds.). Lawrence Erlbaum Associates Publishers, Mahwah, N.J, 247–278. https://doi.org/10.1201/9781410608888.ch12

[23] Robert S. Kennedy, Norman E. Lane, Kevin S. Berbaum, and Michael G. Lilienthal. 1993. Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness. *The International Journal of Aviation Psychology* 3, 3 (1993), 203–220. https://doi.org/10.1207/s15327108ijap0303_3

[24] Helge Lenz and Daniela Schmid. 08.09.2019 - 12.09.2019. Simulation Platform for Reduced Crew Operations — A Case Study. In *2019 IEEE/AIAA 38th Digital Avionics Systems Conference (DASC)*. IEEE, San Diego, USA, 1–7. https://doi.org/10.1109/DASC43569.2019.9081747

[25] Wang Lijing, Xiang Wei, He Xueli, Sun Xiaohui, Yu Jinhai, Zhou Lin, and Sun Gaoyong. 2009. The virtual evaluation of the Ergonomics layout in Aircraft cockpit. In *2009 IEEE 10th International Conference on Computer-Aided Industrial Design And Conceptual Design*. IEEE, Wenzhou, China, 1438–1442. https://doi.org/10.1109/CAIDCD.2009.5375353

[26] Thomas Longridge, Paul Ray, Edward M. Boothe, and Judith S. Burki-Cohen. 1996. *Initiative towards more affordable flight simulators for U.S. commuter airline training*. Royal Aeronautical Society, USA.

[27] R.G. Menendez and J.E. Bernard. 2001. Flight simulation in synthetic environments. *IEEE Aerospace and Electronic Systems Magazine* 16, 9 (Sept. 2001), 19–23. https://doi.org/10.1109/62.949532

[28] Mathias Moehring and Bernd Froehlich. 2005. Pseudo-Physical Interaction with a Virtual Car Interior in Immersive Environments. In *Eurographics Symposium on Virtual Environments*, Erik Kjems and Roland Blach (Eds.). The Eurographics Association, Aire-la-Ville, CH, 185–189. https://doi.org/10.2312/EGVE/IPT_EGVE2005/181-189

[29] W. F. Moroney, D. W. Biers, F. T. Eggemeier, and J. A. Mitchell. 1992. A comparison of two scoring procedures with the NASA task load index in a simulated flight task. In *Proceedings of the IEEE 1992 National Aerospace and Electronics Conference*. IEEE, Dayton, USA, 734–740 vol.2. https://doi.org/10.1109/NAECON.1992.220513

[30] Matthias Oberhauser, Reinhard Braunstingl, Daniel Dreyer, and Ioana Victoria Koglbauer. 2016. Pilots' Interaction with Hardware Controls in a Virtual Reality Flight Simulator. In *Proceedings of the 32nd Conference of the European Association for Aviation Psychology*. European Association for Aviation Psychology, Cascais,Portugal.

[31] Matthias Oberhauser and Daniel Dreyer. 2017. A virtual reality flight simulator for human factors engineering. *Cognition, Technology & Work* 19, 2 (2017), 263–277. https://doi.org/10.1007/s10111-017-0421-7

[32] Matthias Oberhauser, Daniel Dreyer, Reinhard Braunstingl, and Ioana Koglbauer. 2018. What's Real About Virtual Reality Flight Simulation?: Comparing the Fidelity of a Virtual Reality With a Conventional Flight Simulation Environment. *Aviation Psychology and Applied Human Factors* 8, 1 (March 2018), 22–34. https://doi.org/10.1027/2192-0923/a000134

[33] STEFANO PAPA, ANTONIO LANZOTTI, GIUSEPPE Di GIRONIMO, and ALESSIO BALSAMO. 2018. A NEW INTERACTIVE RAILWAY VIRTUAL SIMULATOR FOR TESTING PREVENTIVE SAFETY. In *Computers in Railways XVI : Railway Engineering Design and Operation (WIT Transactions on The Built Environment)*, G. Passerini, J. M. Mera, N. Tomii, and P. Tzieropoulos (Eds.). WIT PressSouthampton UK, Lisbon, Portugal, 367–378. https://doi.org/10.2495/CR180331

[34] Marietta Papadatou-Pastou, Eleni Ntolka, Judith Schmitz, Maryanne Martin, Marcus R. Munafò, Sebastian Ocklenburg, and Silvia Paracchini. 2020. Human handedness: A meta-analysis. *Psychological bulletin* 146, 6 (2020), 481–524. https://doi.org/10.1037/bul0000229

[35] Randy Pausch, Thomas Crea, and Matthew Conway. 1992. A Literature Survey for Virtual Environments: Military Flight Simulator Visual Systems and Simulator Sickness. *Presence: Teleoperators and Virtual Environments* 1, 3 (1992), 344–363. https://doi.org/10.1162/pres.1992.1.3.344 arXiv:https://doi.org/10.1162/pres.1992.1.3.344

[36] Vsevolod Peysakhovich, Louis Monnier, Mélanie Gornet, and Stéphane Juaneda. 2020-03. Virtual reality vs. real-life training to learn checklists for light aircraft. In *Eye-Tracking in Aviation. Proceedings of the 1st International Workshop (ETAVI 2020)*. ISAE-SUPAERO, Université de Toulouse; Institute of Cartography and Geoinformation (IKG), ETH Zurich, Toulouse; Zurich, 47 – 53. https://doi.org/10.3929/ethz-b-000407648

[37] Pornthep Preechayasomboon and Eric Rombokas. 2021. Haplets: Finger-Worn Wireless and Low-Encumbrance Vibrotactile Haptic Feedback for Virtual and Augmented Reality. *Frontiers in Virtual Reality* 2 (2021), 1–15. https://doi.org/10.3389/frvir.2021.738613

[38] Rebekka S. Renner, Boris M. Velichkovsky, and Jens R. Helmert. 2013. The perception of egocentric distances in virtual environments - A review. *Comput. Surveys* 46, 2 (2013), 1–40. https://doi.org/10.1145/2543581.2543590

[39] Savern Reweti. 2014. *PC-based aviation training devices for pilot training in visual flight rules procedures : development, validation and effectiveness*. Doctoral. Massey University.

[40] Andrew Robinson, Katerina Mania, and Philippe Perey. 2004. Flight simulation: research challenges and user assessments of fidelity. In *Proceedings of the 2004 ACM SIGGRAPH international conference on Virtual Reality continuum and its applications in industry - VRCAI '04*. ACM Press, Singapore, 261. https://doi.org/10.1145/1044588.1044644

[41] J. M. Rolfe and K. J. Staples. 1997. *Flight simulation* (repr ed.). Cambridge Univ. Press, Cambridge.

[42] S. Rustamov, E. Gasimov, R. Hasanov, S. Jahangirli, E. Mustafayev, and D. Usikov. 2018. Speech recognition in flight simulator. *IOP Conference Series: Materials Science and Engineering* 459 (2018), 012005. https://doi.org/10.1088/1757-899X/459/1/012005

[43] Shantanu A. Satpute, Janet R. Canady, Roberta L. Klatzky, and George D. Stetten. 2020. FingerSight: A Vibrotactile Wearable Ring for Assistance With Locating and Reaching Objects in Peripersonal Space. *IEEE transactions on haptics* 13, 2 (2020), 325–333. https://doi.org/10.1109/TOH.2019.2945561

[44] Jens Schiefele, Oliver Albert, and Kai Uwe Doerr. 1998. IFR flight simulation in a distributed virtual environment. In *Modeling and Simulating Sensory Response for Real and Virtual Environments (SPIE Proceedings)*. SPIE, Bellingham, United States, 111. https://doi.org/10.1117/12.317567

[45] Daniela Schmid and Neville A. Stanton. 2019. Exploring Bayesian analyses of a small-sample-size factorial design in human systems integration: the effects of pilot incapacitation. *Human-Intelligent Systems Integration* 1, 2-4 (2019),

71–88. https://doi.org/10.1007/s42454-020-00012-0
[46] Samuel B. Schorr and Allison M. Okamura. 2017. Fingertip Tactile Devices for Virtual Object Manipulation and Exploration. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, Gloria Mark, Susan Fussell, Cliff Lampe, m.c. schraefel, Juan Pablo Hourcade, Caroline Appert, and Daniel Wigdor (Eds.). ACM, New York, NY, USA, 3115–3119. https://doi.org/10.1145/3025453.3025744
[47] Alexander Smith, Benjamin Ward-Cherrier, Appolinaire Etoundi, and Martin J. Pearson. 23.10.2022 - 27.10.2022. Feeling the Pressure: The Influence of Vibrotactile Patterns on Feedback Perception. In *2022 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, Kyoto, Japan, 634–640. https://doi.org/10.1109/IROS47612.2022.9981594
[48] Georg Stevenson, Andreas Riener, and Alois Ferscha. 2013. "TactiGlove" – A Guidance System to Effectively Find Hidden Spots in 3D Space. In *Mobile Computing, Applications, and Services*. Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, Vol. 110. Springer Berlin Heidelberg, Berlin/Heidelberg, 80–99. https://doi.org/10.1007/978-3-642-36632-1_5
[49] Peter Thomas, Pradipta Biswas, and Patrick Langdon. 2015. State-of-the-Art and Future Concepts for Interaction in Aircraft Cockpits. In *Universal Access in Human-Computer Interaction. Access to Interaction*, Margherita Antona and Constantine Stephanidis (Eds.). Springer International Publishing, Cham, 538–549.
[50] Kelvin Valentino, Kevin Christian, and Endra Joelianto. 2017. Virtual reality flight simulator. *Internetworking Indonesia Journal* 9, 1 (2017), 21–25.
[51] Danniel Varona-Marin, Jan A. Oberholzer, Edward Tse, and Stacey D. Scott. 2018. Post-Meeting Curation of Whiteboard Content Captured with Mobile Devices. In *Proceedings of the 2018 ACM International Conference on Interactive Surfaces and Spaces* (Tokyo, Japan) *(ISS '18)*. Association for Computing Machinery, New York, NY, USA, 43–54. https://doi.org/10.1145/3279778.3279782
[52] John Vince. 1993. 10 - Virtual Reality Techniques in Flight Simulation. In *Virtual Reality Systems*, R.A. Earnshaw, M.A. Gigante, and H. Jones (Eds.). Academic Press, Boston, 135 – 141. https://doi.org/10.1016/B978-0-12-227748-1.50018-4
[53] Bernhard Weber, Simon Schätzle, Thomas Hulin, Carsten Preusche, and Barbara Deml. 2011. Evaluation of a vibrotactile feedback device for spatial guidance. In *2011 IEEE World Haptics Conference*. IEEE, Istanbul, Turkey, 349–354. https://doi.org/10.1109/WHC.2011.5945511
[54] Eric Whitmire, Hrvoje Benko, Christian Holz, Eyal Ofek, and Mike Sinclair. 2018. Haptic Revolver: Touch, Shear, Texture, and Shape Rendering on a Reconfigurable Virtual Reality Controller. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems - CHI '18*. ACM Press, Montreal QC, Canada, 1–12. https://doi.org/10.1145/3173574.3173660
[55] Guy Williams, Ken Lawrence, and Richard Weeks. 2004. Reconfigurable Flight Simulators in Modeling and Simulation. In *AIAA Modeling and Simulation Technologies Conference and Exhibit (Guidance, Navigation, and Control and Co-located Conferences)*. American Institute of Aeronautics and Astronautics, Providence, Rhode Island. https://doi.org/10.2514/6.2004-5459
[56] Chou Wusheng, Wang Tianmiao, and Hu Lei. 2003. Design of data glove and arm type haptic interface. In *11th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*. IEEE Computer Society, Los Alamitos, Calif, 422–427. https://doi.org/10.1109/HAPTIC.2003.1191332
[57] Binbin Yang, Xiaojun Xia, Shuai Wang, and Lanqing Ye. 2021. Development of flight simulation system based on leap motion controller. *Procedia Computer Science* 183 (2021), 794–800. https://doi.org/10.1016/j.procs.2021.02.131
[58] I. Yavrucuk, E. Kubali, and O. Tarimci. 2011. A low cost flight simulator using virtual reality tools. *IEEE Aerospace and Electronic Systems Magazine* 26, 4 (April 2011), 10–14. https://doi.org/10.1109/MAES.2011.5763338
[59] L. Yu, Z. Xu, and L. Xin. 2019. Research on Reconfigurable Method of Cockpit Simulation for Virtual Training System. In *2019 IEEE 3rd Information Technology, Networking, Electronic and Automation Control Conference (ITNEC)*. IEEE 3rd Information Technology, Networking, Electronic and Automation Control Conference (ITNEC), Chengdu China, 2007–2011. https://doi.org/10.1109/ITNEC.2019.8729557

Received 2023-07-01; accepted 2023-09-22