Designing Mobile MR Workspaces: Effects of Reality Degree and Spatial Configuration During Passenger Productivity in HMDs

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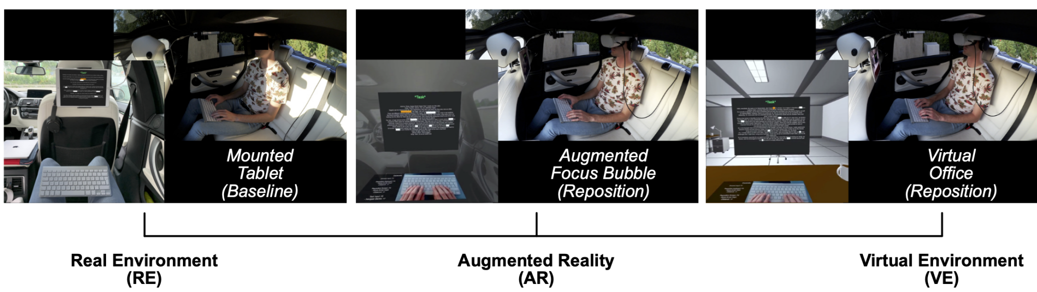

Fig. 1. Mobile Mixed Reality (MR) workspace on the reality-virtuality continuum [31], ranging from the RE condition using a *Mounted Tablet* (left), the AR condition working in an *Augmented Focus Bubble* (middle) simulated in head-mounted displays (HMDs), to the VE condition working in a *Virtual Office* (right) in HMDs.

Virtual Reality (VR) is increasingly used in everyday contexts for a variety of tasks. We particularly look at the confined space for passengers inside cars, where head-mounted displays (HMDs) could complement the prevalent use of mobile devices for work. In a field study (N=19), we tested three mobile workspace setups along the reality-virtuality continuum (*Mounted Tablet*, *Augmented Focus Bubble*, and *Virtual Office*) and let users re-position the virtual keyboard and display while typing on a physical keyboard in a parked car. The results revealed that using HMDs lowered users' awareness of their real surroundings but increased their perceived workload with a performance impairment of text entry rate compared to just using a tablet. Letting users customize their workspace layout improved their perceived performance and decreased pitch-axis head movements for switching between the virtual display and keyboard. This paper discusses challenges and strategies for future work regarding dynamic incorporation of productivity tools, adaptive mixed reality (MR) work environment designs, and optimizing upper thresholds of physical discomfort in mobile MR workspaces.

CCS Concepts: • **Human-centered computing** → **Virtual reality**; *Field studies.*

Additional Key Words and Phrases: mobile workspace, in-car mixed reality, typing task

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1 INTRODUCTION

Commuters often try to use their travel time efficiently by working on portable devices such as tablets and laptops. Anticipating future self-driving cars, the vision of *AutoWork* has sparked a thriving research field [7, 18, 38]. As drivers are freed from driving tasks, they can spend the time gained on productive work. However, the confined passenger space in a car or public transport and distractions from real-world environments, such as passing-by traffic partners, make it difficult to concentrate on work. Prior studies on in-car Virtual Reality (VR) explored the use of head-mounted displays (HMDs) to facilitate mobile working with a variety of designs regarding virtual counterparts of work environments, displays, and keyboards [10, 21, 32]. McGill et al. [28] identified three major challenges: motion sickness, social acceptability, and the confined space itself. Here, we focus on the last factor of the confined space in a productivity scenario. Specifically, we are interested in deploying HMDs to mix realities so that users can transcend their boundaries of a limited car backseat to a secluded virtual environment for concentration while remaining aware of the essentials of physical surroundings. Mixing realities while typing in VR has been studied in terms of how much degree of reality should be incorporated [24], repositioning of a physical keyboard [10], and visualizations of avatar hands [17]. By adapting these solutions to an in-car workspace, we aim to investigate how such a Mixed Reality (MR) design impacts users' performance, sense of presence, perceived workload, and the risk of physical discomfort while using HMDs in the limited car space to conduct productivity tasks in uncontrolled daily environments.

Our study, similar to many previous studies, covers a range of conditions on Milgram's reality-virtuality (RV) continuum [31]. By studying and comparing different reality setups, we aim to understand the benefits and challenges of mobile MR workspaces. In addition, passenger travel environments entail real-world restrictions on mobile work, such as the limited physical workspace and distractions from surrounding vehicles and pedestrians. Therefore, we are interested in how the reality degree and spatial configuration of MR workspaces would impact passengers' physical integrity while being in another virtual space and their productivity when occluding the surrounding information. For the real environment (RE), we chose a mounted tablet instead of a hand-held smartphone to avoid conflicts while using a physical keyboard, creating comparability across conditions. Therefore, we implemented a display-keyboard setup using the *Mounted Tablet* and the wireless keyboard as a baseline. In the Augmented Reality (AR) condition, we embedded this display-keyboard setup using the HMD and the same keyboard as an *Augmented Focus Bubble* into a real-captured 360-degree video of the car backseat. The virtual environment (VE) condition finally embedded the setup into a *Virtual Office* using the same HMD and keyboard. In the two HMD conditions, we further modified the degree of spatial configurability in the layout of the virtual display and keyboard (*Reposition*, *NoReposition*).

We evaluated our prototypes in a field study with 19 participants performing typing tasks in a residential parking lot. The results revealed a weakened awareness of surroundings while working in the car using the HMD. However, this also introduced a higher perceived workload and a slower text entry rate than working on the mounted tablet. In addition, letting users reposition their virtual display and keyboard can diminish their head movements while switching between display and keyboard. Overall, the mounted tablet and keyboard setup is more familiar and preferred. Based on the results, we conclude that today's HMDs are not sufficient yet for passengers' demands of mobile working, e.g., typing on the go. Specifically, we identified three main challenges for future HMD-based passenger productivity with regards to dynamic incorporation of productivity tools, adaptive MR work environment designs, and optimizing upper thresholds of physical discomfort. This work provides valuable insights for future researchers and practitioners who want to apply the HMD to the everyday transit context or shape future transportation spaces into mobile offices.

2 RELATED WORK

2.1 Mobile Work During Transit

Using the car as a mobile office has been well explored for today's business environment [6]. Recent research studied a variety of productivity tasks, such as reading as a passenger [29, 30] or typing and text comprehension as a driver in the car [36, 37]. For example, Schartmüller et al. [37] redesigned the car interior into a mobile workspace to support productivity activities such as typing text on the steering wheel. Anticipating future automated vehicles, they compared two types of display modalities regarding the driver's text comprehension and found the head-up display (reading) to surpass the auditory display (listening) with better productivity performance and lower workload during take-over situations [36]. In contrast, passenger research focused more on the approaches for mitigating motion sickness during non-driving-related activities [5]. Proposed user interface designs include a live video stream of the vehicle trajectory as a reading background [30] or vehicle motion cues in the form of bubbles at the margin of the text [29] shown on smart devices inside the car. However, relatively limited research focused on effective input systems to expand the scope of application scenarios for passenger productivity (e.g., text entry) during their transit.

2.2 Passenger Use of HMDs for Productivity

Given the advances in autonomous driving technology, researchers have envisioned *AutoWork*, the potential future of work in automated vehicles [7, 18, 38]. When anticipating future immersive technology, e.g., ultimate see-through glasses, passengers will probably bring in any accessible HMDs just as they do today with the e-reader, tablet, or laptop for reading and typing text in transit. Prior work analyzed user thoughts and found they can generally imagine using HMDs for working in cars but are concerned with their physical integrity while in VR, given potential conflicts with the limited car space [20]. Furthermore, their productivity performance depends on the virtual work environments they immerse themselves in. Users achieved higher performance in a familiar virtual open-plan office than a secluded virtual natural landscape [21]. While in a public transport space such as an airplane, the passenger's perception of invading other's personal space significantly influenced their preferred layouts of AR-driven virtual screens [32]. However, there are limited studies that evaluated HMD-based productivity with its potential of mixing realities [3], especially blending the essentials of passenger's real surroundings into virtual work environments.

2.3 Text Entry in HMDs

In contrast to much earlier visions of mixed reality workspaces [34], recent work on the virtual office of the future envisions a de-centralized type of mobile workspace facilitated by HMDs [9, 16], However, text entry still is an essential aspect of office work, and many methods for VR have been studied [8]. Prior work shows that the productivity performance in HMDs can be influenced by the reality degree of the avatar hands [17], the mid-air virtual keyboard [1], the position of the virtual and the standard or tablet keyboard [10], and the type of the closed or open physical and virtual environments [35]. Specifically, blending a view of reality into VR significantly corrected the performance impairment of typing [24]. Knierim et al. [17] found that irrespective of the typing experience, typists benefit from seeing their hands while typing in VR. In comparison to abstract representations of hands, realistic hands generate the strongest presence with the lowest workload. Grubert et al. [10] found that users can retain a higher typing speed on a desktop keyboard compared to a tablet keyboard. In the same study, users could also reposition the image of the virtual keyboard and their hands in front of their view direction to maintain reasonable typing performance. Ruvimova et al. [35] found that users preferred the reality in a closed office while VR was preferred in an open office (with distractions). In this work, we adapted these established solutions to the passenger context and tested them in our mobile MR workspaces with various levels of reality degree and spatial configurability.

3 MOBILE MIXED REALITY WORKSPACE DESIGN AND IMPLEMENTATION

3.1 Workspace Design

To achieve the wide coverage of the RV continuum described above, we designed three workspaces in Unity3D (2020.3.15f2). All these workspaces share the same basic setup with a wireless desktop keyboard placed on the user's lap and a Bluetooth noise-canceling headphone that subjects use across all conditions. In total, there are three conditions, one outside the HMD and the other two inside the HMD:

- **RE** *Mounted Tablet* is introduced as the *RE* condition outside the HMD. Here, users read text from a physical display, namely a tablet mounted to the front seat, and type on the physical desktop keyboard while seeing real surroundings in the car backseat (see Figure 1 left).
- **AR** *Augmented Focus Bubble*, as an *AR* condition, mixes two realities inside the HMD. To achieve this simulated see-through AR in the VR HMD, we recorded a 360-degree video from the car backseat as the work environment inside the HMD. We used a 360-degree camera, GoPro MAX, mounted at a similar position as passenger eye levels in the seat behind the co-driver to record the video. We experimented with the same sitting and comparable weather conditions as the shooting configuration. In addition, we added a virtual display and a live camera view of the user's hands typing on the keyboard. The default spatial layout of the virtual display and the keyboard view corresponds to the above-mentioned RE setup, ensuring comparability across non-HMD and HMD conditions. In addition, a sphere with a semi-transparent glass texture[1] is drawn around the user, similar to car window tinting to reduce interference of outside distractions through the darkened glass (see Figure 1 middle).
- **VE** *Virtual Office*, as the *VE* condition, mixes two realities inside the HMD differently. It features a virtual display and a virtual work environment in the form of an open-plan office to foster immersion and productivity in a familiar workspace, as recommended by prior work [21]. All desks in this office are unattended to simulate a closed office for the single user. We selected a traditional desk setup including the same virtual display. On top of this virtual office, we incorporated the same live camera view of the user's hands typing on the keyboard. The same default spatial layout applies here for comparability (see Figure 1 right).

In this work, we refer to the *Augmented Focus Bubble* as the AR condition and the *Virtual Office* as the VE condition according to the design of work environments inside the HMD. Each condition contains a mix of two realities. These two ways of mixing realities share the same virtual display (VE) and live keyboard view (RE) but differ in the work environment, namely the simulated car interior (RE) and the virtual office (VE) respectively.

3.2 Workspace Configuration

To support typing in VR through visual representations of the physical keyboard and the hands, as suggested in prior work [10, 17], we added a keyboard camera view, which also is adjustable, just as the virtual display:

3.2.1 Providing a Keyboard Camera View. A webcam is mounted to the car ceiling and points to the user's lap. The live feed recorded by the webcam is then shown on the keyboard view window in the HMD, with a hardly noticeable latency of about 1-2 frames ($40 - 80ms$). The image can be resized and positioned within this view window as needed using digital zoom and pan. Using the

[1] https://assetstore.unity.com/packages/2d/textures/texture-182052, last visited August 11, 2022

arrow, + and - keys, users can position and scale the frame they see on their virtual keyboard window exactly to where they need it, for example pointing directly at the physical keyboard on their lap. This keyboard camera view lets users see both the keyboard and their real hands while typing inside the HMD. We expect this real-world view to enhance typing performance and make the setup consistent with the non-HMD condition. Using this ceiling-mounted camera instead of an HMD-mounted one, we minimized additional weight on users' heads.

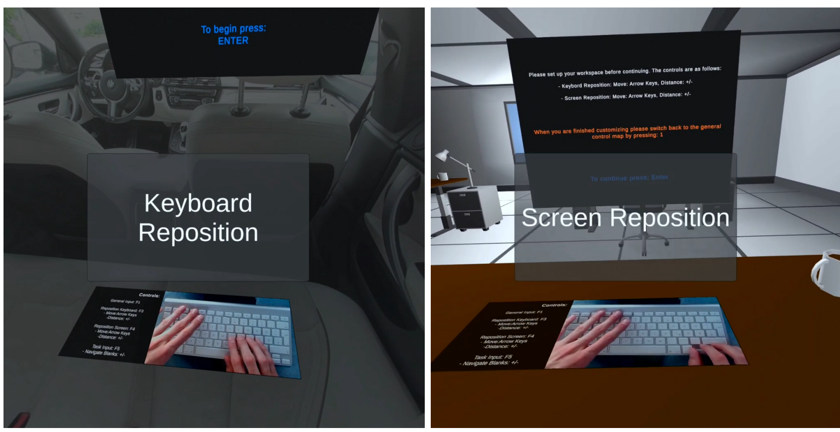

Fig. 2. Keyboard reposition in the *Augmented Focus Bubble* (left) and display reposition in the *Virtual Office* (right). A list of all defined control keys was displayed next to the keyboard throughout the study as references.

3.2.2 Repositioning the Virtual Display and Keyboard View. In both AR and VE conditions, users can freely reposition the virtual display and the keyboard view on the X-, Y- and Z-axis (world coordinates) inside the HMD. As a default setting, the inner dimensions of the car were transferred 1:1 into the HMD conditions. The distances were measured relative to the HMD position when the user sits in a car, and the keyboard view is displayed approximately at the same position as the physical keyboard in real life. Similarly, the virtual display is at the same position at which the physical tablet is mounted. Both the virtual display and keyboard view can be positioned freely using the arrow keys and + or - (for distance) on the keyboard (see Figure 2). This spatial *Reposition* aims to decrease the distance between the virtual display and the keyboard camera view, further reducing users' head movements by looking up and down. Moreover, letting users customize their workspaces represents an example of the advantages HMDs can have over conventional integrated displays in cars. By using the ceiling-mounted camera view of the keyboard and the *Reposition* function, we let users adjust their workspace layouts which ensure minimal head motion and thus prevent motion sickness in the passenger context. To investigate the impact of this spatial configurability on the mobile MR workspace, we introduced a control condition *NoReposition*, ensuring comparability between non-HMD and HMD conditions.

4 USER STUDY

We conducted a field study in a parked car to evaluate and compare our different concepts. The study conformed to the regulations set forth by the institutional review board.

4.1 Study Design

Our study uses a mixed (between- and within-subjects) design. We defined two independent factors: *Reality Degree* and *Spatial Configuration*. There are three levels of *Reality Degree* along the

RV continuum: *Mounted Tablet*, *Augmented Focus Bubble*, and *Virtual Office*, which were studied within-subjects. *Spatial Configuration* has two levels (only in *Augmented Focus Bubble* and *Virtual Office*), *Reposition* and *NoReposition*, which were studied between-subjects. We omitted the tablet condition with spatial reposition, e.g., holding the tablet and typing on the embedded keyboard. Such usage induces additional physical demand, reduces typing speed using a tablet keyboard [10], and interferes with comparability across conditions. Participants were randomly assigned to the two groups: *Reposition* (n=10) and *NoReposition* (n=9). Each participant experienced the conditions *Mounted Tablet*, *Augmented Focus Bubble*, and *Virtual Office* in a randomized order.

4.2 Study Task

We chose a blank filling task using text and audio from the European language framework level English B2[2], as suggested in prior work [37]. Similar to a transcription task, the full text was read out over the headphones and participants had to listen and fill the blanks consecutively. On the screen, they could navigate by pressing the + key for the next blank and – for the previous. By default, the first blank in each task was selected and highlighted in orange, while the remaining blanks were shown in white (see Figure 3 left). In each condition, we asked the participants to complete three different blank filling tasks in a row with a four-second interval in between. In total, we selected nine blank filling tasks and used them for both groups. On average, each task had 8 blanks (SD = 1.05) and 52.11 characters (SD = 17.28), and lasted 90.74 seconds (SD = 4.21). They differed in content but shared the same structure and format.

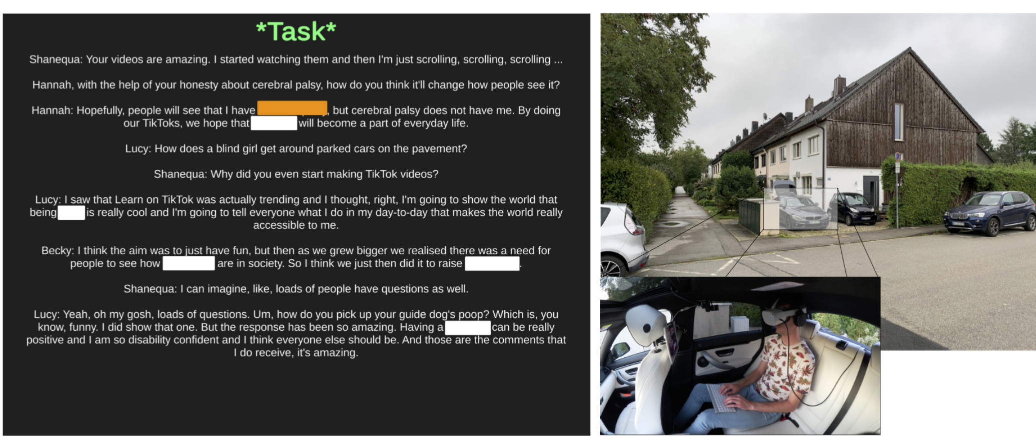

Fig. 3. User Interface for the blank filling task, with the first blank selected and shown in orange (left). Testing environment for the field study, shown from the street view (top) and inside the car (bottom).

4.3 Study Setting and Apparatus

The study was set in a BMW 4 Series F36 Gran Coupe parked in a suburban residential area (see Figure 3 right). The street environment was overall quiet with sparse traffic flow and only a few pedestrians and cyclists that passed by in the front and on the right ($2 - 10m$ away from the car) during the study. The number of these real-world distractions was uncontrolled and therefore randomized for all conditions. We set up a *Dell G5* laptop (GTX 2070) in the car trunk and ran the Unity3D builds on it to display them either on the tablet or the HMD. For the *Mounted Tablet*

[2] https://learnenglishteens.britishcouncil.org/level/b2-cefr/term, last visited August 11, 2022

condition, a 10.5-inch iPad Pro was mounted to the metal supports of the front seat's headrest with a tablet holder. The iPad was running Duet Air[3]. It was connected via USB to the laptop in order to be used as an external display. The cable connection allowed for minimal latency and high reliability compared to a wireless connection. For the two HMD conditions, we used an Oculus Quest 2 (a singular fast-switch LCD display with an 1832 x 1920 per eye resolution, 120 Hz refresh rate, 104° horizontal and 98° vertical field-of-view) and connected it to the laptop via USB cable in the Link mode. For the audio, we used a wireless Srhythm NC25 noise-canceling headphone. For typing in the car, we used a wireless Apple Magic Keyboard (German layout). During the study, we asked the participants to type on the keyboard placed on their lap. To broadcast the keyboard view, we used a HAMA c600 Pro full HD webcam (1920 x 1080 resolution). The camera was mounted to the car ceiling via a suction cup holder. The webcam's perspective was chosen so that the middle of the frame was pointing at the edge of the seat, going down to the footwell. The frame thus covered the area in which participants placed the keyboard on their lap during the study. This keyboard camera view was present in all the four HMD conditions, *Augmented Focus Bubble* and *Virtual Office*, with *Reposition* and *NoReposition*.

4.4 Measures

We measured the effects of the mobile MR workspaces using both quantitative and qualitative measures. As a quantitative measure, we examined the participant's typing performance as their **entry rate** in words per minute (wpm) and their **error rate (ER)** [2]. In the HMD conditions, *Augmented Focus Bubble* and *Virtual Office*, we also measured **head motion** as the cumulative amount of head movements around the horizontal (yaw) and vertical (pitch) axes, and the **workspace spatial configuration** as the X-, Y-, and Z-axis vectors of the re-positioned virtual display and keyboard. By measuring the head motion, we aim to quantify the impact of *Spatial Configuration*, comparing *Reposition* to *NoRepostion*. Therefore, we focused on the head motion in two *Reposition* conditions, *Augmented Focus Bubble* and *Virtual Office*, rather than the *Mounted Tablet* condition without *Reposition*. The qualitative measures were:

- **Visual discomfort**: "Please rate your general visual discomfort (e.g., feelings of tiredness, soreness, irritation, watering and/or burning in eyes) during the task." 1 = no discomfort, 7 = pain [13].
- **Neck fatigue**: "Please rate your neck fatigue during the task." 0 = no fatigue, 10 = extremely strong fatigue based on the Brog CR10 scale [12].
- **NASA-Task Load Index (TLX)**: A measure of mental demand, physical demand, temporal demand, performance, effort, and frustration [11].
- **IPQ presence questionnaire**: A measure of general presence, spatial presence, experienced realism, and involvement [40].
- **Concentration**: "Please rate your concentration level during the task." 1= extremely distracted, 7= extremely concentrated.
- **Awareness**: "Please rate your awareness of changes in your real surroundings during the task." 1= extremely unaware of, 7= extremely aware of.
- **User rankings**: "Please rank the three conditions you experienced in order of preference - which would you most prefer to use day to day?" This question was asked in the final interview after the participant experienced all three conditions.

[3]https://www.duetdisplay.com/air, last visited August 11, 2022

4.5 Procedure

Before the start of the study, the experimenter explained the study goal of testing passenger productivity performance while using smart devices in the car. After giving their consent, participants were invited to sit in the backseat behind the co-driver seat. The experimenter informed them about a hygiene concept that required disinfection and ventilation throughout the study. Once seated alone in the fixed position, participants could remove their masks to reduce interference. They then filled out a demographic questionnaire on a laptop. To start, the experimenter presented a slide show (with prepared transcript) introducing the three levels of *Reality Degree* implemented in the tablet and HMD, a tutorial on *Spatial Configuration* using the keyboard (where applicable), and how to navigate and enter text in the blank filling task. Participants were given the opportunity to ask questions concerning the study task. Next, the study started with one of the three reality levels in randomized order. For the *Augmented Focus Bubble* and *Virtual Office* using HMDs, the participant put on the headset and the headphone and put the keyboard on their lap. The keyboard view window (zoom and pan) was then set up by the experimenter. The *Reposition* group could additionally adjust the spatial positions of their keyboard view and virtual display via the specified keys. After configuration and pressing the Enter key, the blank filling task started. While listening to the audio and seeing the transcript on the virtual display, participants in both *Reposition* and *NoReposition* were asked to fill out the blanks by typing on the keyboard. For the baseline *Mounted Tablet*, they followed the same procedure to complete the same task but without wearing the HMD. Instead, the text was shown to them on the tablet display mounted on the front seat's back in front of them. After each condition, the participants were asked to fill out a questionnaire asking for perceived workload, presence, concentration, and awareness of surroundings. After experiencing all three conditions, the experimenter conducted a semi-structured interview with each participant, asking for overall opinions and suggestions for future mobile MR workspaces. Each participant was compensated with 10€. In total, the study took about one hour.

4.6 Participants

In total, we recruited 19 participants (10 male, 9 female) from institutional mailing lists. They were aged from 19 to 56 years ($M = 25.1, SD = 10.2$). The majority had no (n=9) or limited (n=9) prior VR experience and traveled less than $10,000km$ (n=14) per year with each journey lasting less than 30 minutes (n=10) before Covid-19. During the transit, twelve of them had mobile working experience while seven had never worked as a passenger on the way. On a scale from 1 (very poor) to 10 (very good), participants rated their typing skills slightly good when seeing the keyboard ($Mdn = 7.0, SD = 2.19$), but slightly poor ($Mdn = 4.0, SD = 2.91$) without seeing it, i.e., typing blind. Specifically, the majority (n=16) rated typing blind with worse performance than seeing the keyboard. Two participants found no differences and rated both typing manners with the highest score of 10 (P14, P19). Only one participant (P17) rated typing blind with higher proficiency, a score of 5, than typing with seeing keyboards, 2. All of them were familiar with the used keyboard layout. Seven used a Windows system and twelve a Mac more often.

5 RESULTS

For parametric data, we performed a two-factor mixed design ANOVA in JASP [14] with Greenhouse-Geisser correction when the assumption of sphericity is violated. When the results were found significant, we used Bonferroni for post-hoc correction. For non-parametric data, we used the mixed factor align-and-rank ANOVA [42]. For effect size, partial eta-squared (η_p^2) is reported. Significance is reported if $p < .05$.

5.1 Quantitative Measures

5.1.1 Typing Performance. Regarding the mean text entry rate, there was no statistically significant interaction effect between *Reality Degree* and *Spatial Configuration* ($F(2, 110) = 0.57, p = .57, \eta_p^2 = 0.01$). However, we found a significant main effect within *Reality Degree* ($F(2, 110) = 24.59, p < .001, \eta_p^2 = 0.309$). Bonferroni-corrected post-hoc tests showed that entry rate was significantly slower in the *Virtual Office* condition compared to the *Mounted Tablet* ($t = 6.76, p < .001$) and *Augmented Focus Bubble* ($t = 5.00, p < .001$) (see Figure 4 left). Regarding the error rate, using the Greenhouse-Geisser correction, there was no significant interaction effects between the two degrees ($F(1.10, 60.6) = 0.413, p = .54, \eta_p^2 = 0.01$). Neither were there significant main effects within *Reality Degree*: *Mounted Tablet* – *Augmented Focus Bubble* ($t = -1.37, p = .516$); *Mounted Tablet* – *Virtual Office* ($t = .88, p = 1.0$); *Augmented Focus Bubble* – *Virtual Office* ($t = 2.25, p = .079$) and *Spatial Configuration* ($t = 0.72, p = .474$).

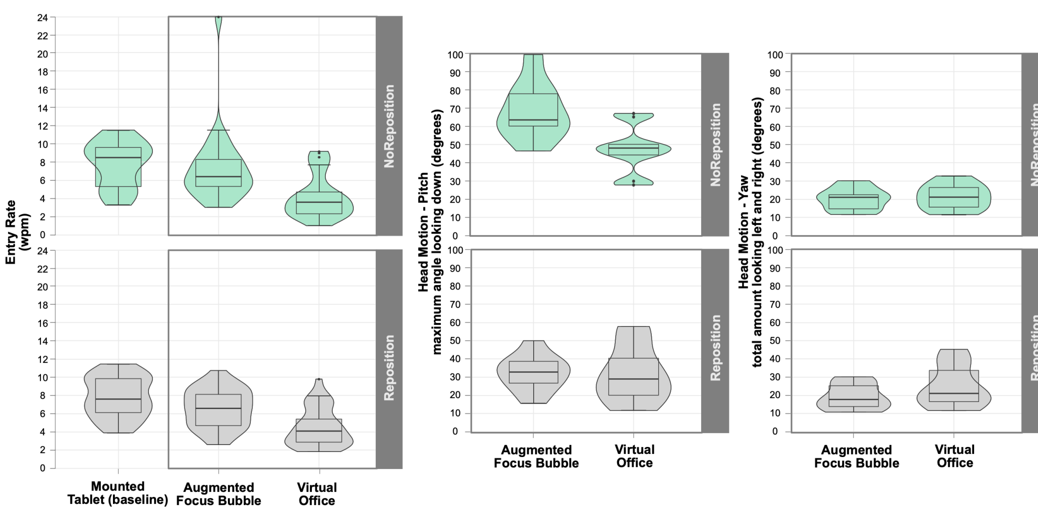

Fig. 4. Entry rate (left) for each condition and across the *Spatial Configuration* degree (top = *NoReposition*, bottom = *Reposition*). For *Mounted Tablet*, we used the same setup in both groups as a baseline. Maximum vertical pitch-axis (middle) and total horizontal yaw-axis (right) *head motion* in HMD conditions.

5.1.2 Head Motion. Regarding the mean head motion, there was no significant interaction effect but main effects within *Reality Degree* ($F(1, 17) = 7.581, p = .014, \eta_p^2 = 0.308$) and *Spatial Configuration* ($F(1, 17) = 16.536, p < .001, \eta_p^2 = 0.493$). Post-hoc tests showed that the participants looked down on average with less head movements in *Reposition* than in *NoReposition* ($t = 4.07, p < .001$) (see Figure 4 middle). In addition, they rotated heads around the horizontal axis more in *Virtual Office* than in *Augmented Focus Bubble* ($t = -2.75, p = .014$) (see Figure 4 right).

5.1.3 Workspace Spatial Configuration. In the *RePosition* conditions, our participants in the *Augmented Focus Bubble* on average moved the virtual display 0.5*cm* towards the right ($SD = 1.2$), 7.4*cm* down ($SD = 8.0$), 0.6*cm* away ($SD = 9.7$) and adjusted the live camera view of the keyboard 0.8*cm* towards the right ($SD = 0.9$), 16*cm* up ($SD = 11.4$), 2.3*cm* away ($SD = 8.0$). In comparison, in the *Virtual Office*, they on average moved the virtual display 0.5*cm* towards the right ($SD = 0.9$), 9.1*cm* down ($SD = 7.9$), 4.6*cm* away ($SD = 6.9$) and adjusted the keyboard view 0.9*cm* towards

Table 1. Means and standard deviation (*SD*, in brackets) of visual discomfort, neck fatigue, IPQ presence (overall score), and concentration across all conditions.

Reality Degree	Configuration Group	Visual Discomfort	Neck Fatigue	IPQ Presence	Concentration
Mounted Tablet	n/a	2.22 (1.72)	1.89 (1.05)	n/a	5.44 (1.01)
	n/a	2.10 (1.29)	1.80 (0.92)	n/a	4.50 (1.72)
Augmented Focus Bubble	NoRep	2.67 (1.73)	2.11 (1.27)	4.73 (0.64)	5.67 (1.12)
	Rep	3.20 (1.14)	2.10 (1.10)	4.69 (0.43)	4.90 (1.20)
Virtual Office	NoRep	2.56 (1.51)	2.22 (1.48)	4.55 (0.90)	5.67 (0.87)
	Rep	3.30 (1.16)	2.30 (1.16)	4.36 (0.59)	5.10 (1.20)

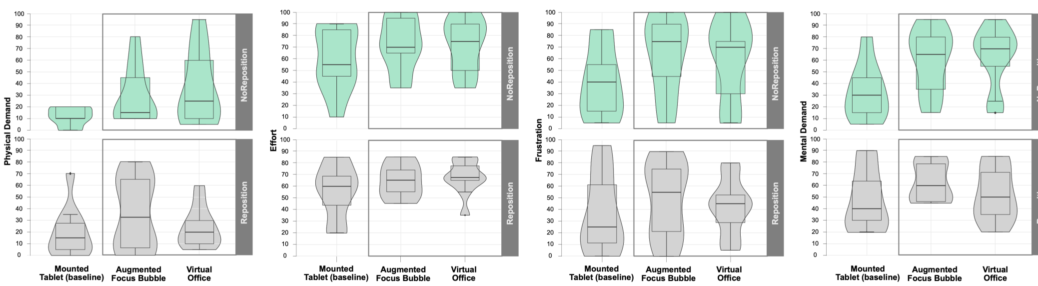

Fig. 5. Four *TLX Workload* subscales that showed significant differences across all conditions.

the right ($SD = 1.3$), 13.8*cm* up ($SD = 9.2$), and 2.5*cm* closer ($SD = 15.0$). However, we found no significant difference between these two conditions in the HMD.

5.2 Qualitative Measures

5.2.1 Perceived Workload. There were no significant interaction effects between the two degrees nor significant main effects of a single degree for visual discomfort ($F(2, 51) = 0.612, p = .546$) and neck fatigue ($F(2, 51) = 0.068, p = .934$). Table 1 shows a lower than moderate level of visual discomfort and neck fatigue on average across all conditions. For overall raw-TLX workload, there were no significant interaction effects but a main significant effect on *Reality Degree* ($F(1.865, 31.699) = 11.005, p < .001, \eta_p^2 = 0.393$). Post-hoc tests emphasized the difference between the HMD and non-HMD conditions, which means typing in *Augmented Focus Bubble* ($t = -4.36, p < .001$) and *Virtual Office* ($t = -3.68, p = .002$) caused the participants significantly more overall workload than *Mounted Tablet*. The TLX physical demand mirrored these results, while we only found significant differences between *Virtual Office* and *Mounted Tablet* for TLX effort ($t = -2.70, p = .032$), as well as between *Augmented Focus Bubble* and *Mounted Tablet* for TLX frustration ($t = -2.90, p = .019$). We only found a significant interaction effect for TLX mental demand ($F(1.931, 32.828) = 5.287, p = .011, \eta_p^2 = 0.237$). Post-hoc tests revealed that *Mounted Tablet* created significantly less mental demand than *Augmented Focus Bubble* ($t = -5.29, p < .001$) and *Virtual Office* ($t = -4.25, p < .001$), which is affected by *NoReposition* ($t = -4.79, p < .001$ and $t = -5.17, p < .001$, respectively). Figure 5 shows these identified significant results.

5.2.2 Presence, Concentration, and Awareness. There were neither significant interaction effects nor main effects regarding IPQ presence and concentration (see descriptive statistics in Table 1). There was, however, a main effect on *Reality Degree* ($F(2, 51) = 4.644, p = .014$), which emphasized significant differences between HMD and non-HMD conditions. Specifically, working in *Augmented Focus Bubble* ($t = 2.713, p = .024$) and *Virtual Office* ($t = 2.477, p = .043$) significantly diminished

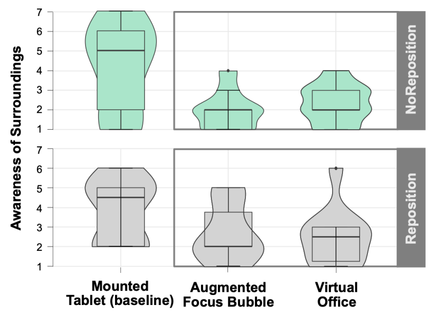

Fig. 6. *Awareness* of surrounding real environments when working inside the car across all conditions.

the participants' awareness of their real surroundings compared to *Mounted Tablet*, irrespective of the *Spatial Configuration* (see Figure 6).

5.3 Interviews

We followed a thematic analysis [4] to code the participant's subjective comments. The identified three themes will be illustrated below with participants' representative quotes under their IDs. The authors translated all quotes from the participants' mother tongue to English.

5.3.1 Tablet Was Familiar and Preferred. *Mounted Tablet* was preferred (15/19) over *Augmented Focus Bubble* (11/19) and *Virtual Office* was ranked last (11/19). Some participants stated that they *"are used to normal displays" (P3, P13)* and found the keyboard is *"more visible" (P16, P18)* in the *Mounted Tablet* condition than in the HMD. Our participants reported that compared to the tablet, the *Virtual Office "helped with concentration" (P7, P10, P14, P16, P17)* while their opinions differed regarding *Augmented Focus Bubble* as *"it was still distracting because of the movements in the background" (P7).* In comparison, *Mounted Tablet* allowed for *"lots of distractions" (P3, P10)* from their real surroundings. When asked if they would use such a mobile workspace application in future transit on a scale from 1 (not at all) to 7 (totally), our participants preferred the tablet ($M = 5.74, SD = 1.59$) to HMDs (*Augmented Focus Bubble*: $M = 2.74, SD = 0.99$; *Virtual Office*: $M = 2.79, SD = 1.65$). Motion sickness induced while working on the go was a shared concern across all conditions irrespective of the display type. Additionally, some participants expected future HMD technology to surpass today's tablet for mobile work, e.g., *"if VR can solve carsickness while working on the way it will be better" (P14).*

5.3.2 Configuration Was Relevant to Perceived Performance. Since this study took place in the parked car, our participants reported none to limited general discomfort that affected them during the task. Their reports on a scale from 1 (not at all) to 7 (extremely uncomfortable) ranged from *Mounted Tablet* with *NoReposition*: $M = 1.0, SD = 0$ to *Augmented Focus Bubble* with *Reposition*: $M = 2.20, SD = 1.40$. The main criticism about the tested HMD was its heavy weight (5/19). Other complaints included the low resolution (*P4, P13*), the usage over time (*P8*), vertical head motion (*P10*), and unfamiliar usage like adjusting the headset (*P15*). Consequently, our participants reported on average a moderate level of performance across all HMD conditions. Specifically, their self-rated performance was slightly higher in the *Reposition* conditions (*Augmented Focus Bubble*: $M = 4.10, SD = 1.37$; *Virtual Office*: $M = 4.50, SD = 1.18$) than the *NoReposition* (*Augmented Focus Bubble*: $M = 3.22, SD = 1.39$; *Virtual Office*: $M = 3.0, SD = 1.32$). Most participants attributed their performance in the *Reposition* conditions to the fact that *"having keyboard and screen nearer helped a lot" (P8, P10, P14)* or *"keyboard camera always in the field of view is really good for performance, which* *is an advantage over mounted tablet" (P19).* Consistently, the others in the *NoReposition* conditions named the tiring head motion as *"looking from keyboard to screen was complicated" (P1, P5).*

5.3.3 Design Future HMDs Specific for Mobile Work. Our participants suggested to improve HMD-based mobile workspaces considering: resolution (8/19), keyboard camera view (6/19), and the design of virtual work environments (4/19). The low resolution of the HMD and web cam challenged our participants in the study, e.g., *"The HMD's sharpness was tiring for the eyes and it was hard to read the text" (P4).* Likewise, it influenced the camera view of the keyboard, which inspired some to demand *"more options for customizing the workspace layout like tilting its angles would be nice" (P15)*, *"enlarging keyboard labeling" (P10)*, and *integrating a keyboard holder into the car (P7, P14).* Regarding the ever-changing real environment that forms the background when typing on the way, the majority suggested a rendered keyboard (11/19) which can be *"more streamlined and have no interference from sunlight" (P14, P15, P18)".* In contrast, two participants favored the implemented keyboard view due to *"a combination of seeing and feeling is better with a camera view" (P16).* In addition, one participant mentioned the HMD fading from consciousness while working in the *Augmented Focus Bubble*, e.g., *"The bubble lets me forget that I am wearing a VR headset" (P3).*

6 INSIGHTS FOR MOBILE MIXED-REALITY WORKSPACES

Based on the results, we identified three main challenges in future research and practices for mobile MR workspaces. The challenges are: i) dynamic incorporation of productivity tools, ii) adaptive MR work environment designs, and iii) optimal upper threshold of physical discomfort. Below, we present more detailed questions for such systems, focusing on the identified empirical evidence and participant feedback.

6.1 Incorporating Productivity Tools Dynamically to Enhance Performance

The study results showed that the non-HMD (tablet-based display-keyboard) setup significantly outperformed the HMD conditions regarding users' entry rate. However, the *Spatial Configuration* in the HMD enhanced users' perception of performance and significantly diminished their head movements for looking up and down. In line with Grubert et al. [10], letting passengers customize their MR workspace in HMDs can improve their overall productivity performance. Our results further raised two questions: i) when and ii) at which degree of reality should productivity tools be incorporated into the virtual workspace during transit? For example, we envision additional customization of the current keyboard view like the *Reality Degree* itself, such as changing from the real-time camera view to an augmented keyboard [25] or "rendered virtual keyboard" in overexposure and underexposed situations on the road, or "tilting" the keyboard view. Furthermore, extending the *Reposition* from adjusting spatial positions of the keyboard view and the virtual display, we suggest systematically exploring potential dimensions of the *Spatial Configuration* degree, such as reorientation and resizing.

6.2 Adapting MR Work Environment Designs to Different Transport Scenarios

We found significantly higher overall workload perceived by the passengers when typing in HMDs. This is attributed to the higher level of effort, frustration, physical, and mental demand in the implemented AR and VE conditions compared to using the tablet. Meanwhile, this HMD users' higher workload came along with a significantly lower awareness of their real surroundings. The implemented virtual work environments, *Augmented Focus Bubble* and *Virtual Office*, lowered users' awareness of distracting streets however without significant improvement of their sense of presence and concentration in the productivity task. Comparing these two levels of *Reality Degree*, we found significantly more horizontal head motion in the *Virtual Office* than *Augmented Focus*

Bubble. Users attempted to look around more in a rendered environment that appears differently from their real surroundings. It remains unclear how much of this has to be attributed to a novelty effect. We question how MR work environments need to adapt to distinct travel environments in cars and other transportation for keeping essential awareness of users' physical surroundings while maintaining presence and concentration in virtual workspaces. We envision that passengers can access different amounts of the RE in virtual workspaces [24], depending on traffic density, vehicle dynamics, and other passengers in the given transport scenario. For example, MR workspaces can blend in a partial RE when passengers use the headset in chauffeured drives with distracting stop-and-go traffic while blending in a full RE when passengers pass by a secluded natural landscape on the train with sparse traffic flow.

6.3 Upper Thresholds of Physical Discomfort

Our participants preferred the familiar tablet-based display-keyboard setup for typing in the car over the HMD-based workspace. They complained about the resulting visual discomfort and neck fatigue after using VR headsets (for around 13 minutes), although the disturbance was relatively weak (see Table 1) in this static study setup. The participants attributed this physical discomfort to general issues in the HMD such as its *"heavy weight"* and *"low resolution"*, rather than the confined space of the car backseat. In future mobile MR workspaces, physical discomfort will be a dominant factor for passengers to drop out of the experience in HMDs. The discomfort of the eyes and the head should be considered when designing mobile productivity applications in HMDs. Defining an upper threshold for the task duration is essential, which can differ across task types. For example, compared to typing, the user-requested video calls with colleagues in VR [20] might allow a higher threshold of exposure time to HMDs, as users can look around without frequently switching between the virtual display and keyboard throughout the meeting. Alternative strategies can be notifications for a break when the VR system detects an over-time usage. Likewise, different input techniques can support text entry across task types, from keyboard-based for long-term typing to gaze-assisted voice-based note-taking [15]. Depending on the task workload, these techniques might impact discomfort and are worth further investigation. For future mobile MR workspaces, designers can optimize a reasonable upper threshold of physical discomfort by exploring different input techniques matching the targeted productivity tasks over time and scenarios.

7 LIMITATIONS AND OUTLOOK

Today's HMDs are limited in mobile work regarding their weight, field of view, and resolution. This hinders the long-term usage with frequent head motion and induces motion sickness. Newer headsets with higher resolution and lighter weight might change the results, e.g., by sharpening the displayed text and easing physical discomfort. In this study, we chose the Quest 2, considering its accessibility and wide popularity among users[41]. In day-to-day mobile work, this VR headset could be the first adopted by users in the car. We only implemented three discrete levels of reality in our design of virtual work environments. However, we envision a continuous transition along the RV continuum for the design of work environments and the layout of a virtual display and keyboard. For example, the vehicle system could trigger a real-to-virtual workspace transition to ensure the passenger's higher concentration in HMDs and fewer external disturbances when a construction site is detected along the vehicle's route. Similarly, HMD users could trigger a virtual-augmented workspace transition for higher awareness of surroundings when faced with an on-boarding passenger in a shared car [22] or needs to interact with the car interior like turning off the window [19]. We call for future research utilizing Oculus Passthrough API [33] or new MR headsets to explore these continuous transitions with higher visual quality and better ergonomics experience, addressing the challenges of real-world awareness in passenger use of HMDs. Additionally, we only achieved a moderate level of presence in the HMD conditions. Some participants complained about the boring *Virtual Office*. Future work can explore more engaging work environments and workspace layouts such as virtual multi-display environments [26], empowering users with a higher level of interactivity.

In contrast to a lab study, our field study used a more realistic setting, in which users experienced dynamic lighting conditions and distractions in the parking space, such as passing pedestrians. These important aspects of ever-changing real environments provide contextual challenges and implications for future *AutoWork* [7]. Likewise, the parking environment represents realistic transport scenarios, passengers working on smart devices while waiting for others or traffic jams. The results showed that the tablet was favored over headsets while the car is static. A follow-up study could replicate the experiment in a moving vehicle, with additional synchronized visual cues around MR workspaces in the VR headset to examine motion sickness as shown in the prior work [27]. Today when using headphones along the way, passengers adjust noise-cancellation levels dependent on their needs to hear real-world sounds. For example, when they get on board public transport at the beginning, they may turn off noise cancellation to beware of passersby and increase to a high-level noise cancellation when settled in the middle of the travel. Passengers' real-world awareness differs across transport scenarios in transit. In specific, we envision various MR workspace setups, covering a variety of passenger scenarios (public transport like trains and airplanes) with the complexity of vehicle dynamics (stop-and-go traffic and pitch-/yaw-/roll-axis motion) and seatmates (number of co-located passengers and seating positions [39]).

Nonetheless, the testing environment was limited as the car was parked and only hosted a single user. Motion sickness and social acceptability [28] are worth further investigation when the vehicle is moving or shared with the public. For example, the placement of the virtual display and keyboard will probably need to consider vehicle dynamics and other passengers [32]. Li et al. [23] demonstrated that passengers' wider head movements in the HMD induce motion sickness during the transit and a trade-off between the engagement and the motion sickness is ±50 degrees around the horizontal and vertical axes. In our study, the *Virtual Office* on average satisfies this range better than the *Augmented Focus Bubble* (as shown in Figure 4 left), while users' awareness of surroundings was similar in both AR and VE conditions. Concerning users' broader head movements in HMDs, the question remains how we can alter the spatial position of different parts of REs and VEs and at which degree of reality we should represent them for an optimal trade-off between motion sickness and essential awareness of physical surroundings. We call for future research examining motion sickness and real-world awareness during passenger activities in HMDs.

Finally, individual differences in English language proficiency that we did not measure in the demographics might have influenced typing performance. Besides, a larger sample size with various levels of prior VR experience can influence the results and change the statistical significance.

8 SUMMARY AND CONCLUSION

When anticipating HMDs as the ultimate brought-in device for mobile working, it can be difficult for the passenger to concentrate on productivity tasks within confined and less controllable surroundings. To address the problem, we built three mobile MR workspaces on the Reality-Virtuality continuum, which cover three levels of *Reality Degree* (*Mounted Tablet*, *Augmented Focus Bubble*, *Virtual Office*) and the *Spatial Configuration* option (*NoReposition*, *Reposition*). In a field study, we invited 19 rear-seat passengers to perform a typing task using a physical keyboard and an HMD in comparison to the mounted tablet. The results revealed that their performance regarding text entry rate was impaired in the HMD, while configuring the workspace layout positively influenced their perception of performance. The implemented MR work environment design of *Augmented Focus Bubble* and *Virtual Office* induced a higher workload but lowered the passenger's awareness of their real surroundings during the task. Although our participants preferred the tablet-keyboard setup over the HMD usage for mobile typing, they attributed the problems to the heavy weight and low resolution of today's HMDs and suggested potential advantages of future HMD-based mobile workspaces, such as personalizing their layout or diminishing passenger carsickness. This research can help HMD users to diminish their head motion when switching between the display and keyboard and become less aware of their ever-changing surroundings in *AutoWork*. It demonstrates a novel use of spatial configurability in MR workspaces and creates opportunities for new mobile working setups.

Based on these results, we discussed three main challenges for future mobile MR workspaces: i) When and at which degree of reality should the productivity tools be incorporated inside HMDs to enhance performance? ii) How should MR work environment designs adapt to different types of real surroundings across transportation means? and iii) What is a reasonable upper threshold of physical discomfort across tasks and input techniques? These identified challenges provide concrete starting points for future research and practical developments of mobile MR workspaces.

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