A Touch of Realities: Car-Interior-Based Haptic Interaction Supports In-Car VR Recovery from Interruptions

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Figure 1: Our interactive armrest enables haptic and visual traces across real and virtual environments, which help users recall prior presence in everyday in-car VR.

ABSTRACT

Real-world interruptions will challenge virtual reality (VR) users in future everyday transport. For example, while passengers are immersed at a virtual beach, an incoming phone call might interrupt their presence and relaxation. We investigated how to help users recover from such interruptions by exploring haptic and visual cues that help them recall their prior presence in VR. We approached this by developing a passive haptic display for rear-seat passengers using an interactive armrest. In a lab study (N=30), participants played with virtual sand to relax, feeling the changes in the real armrest and seeing them on the virtual beach. We compared this multi-sensory experience to the single modalities (just visuals or just haptics). The results showed that the multi-modal experience lowered awareness of the armrest more and fostered a feeling of connectedness to the virtual world after real-world interruptions. We propose using car-interior-based haptic displays to support in-car VR recovery from interruptions.

CCS CONCEPTS

• **Human-centered computing → Empirical studies in ubiquitous and mobile computing**; *Virtual reality*.

KEYWORDS

in-car VR, haptic display, interruption recovery, HMD

ACM Reference Format:

Jingyi Li, Linda Hirsch, Tianyang Lu, Sven Mayer, and Andreas Butz. 2022. A Touch of Realities: Car-Interior-Based Haptic Interaction Supports In-Car VR Recovery from Interruptions. In *Mensch und Computer 2022 (MuC '22), September 4–7, 2022, Darmstadt, Germany*. ACM, New York, NY, USA, 11 pages. https://doi.org/10.1145/3543758.3543768

MuC '22, September 4–7, 2022, Darmstadt, Germany

ACM ISBN 978-1-4503-9690-5/22/09…$15.00
https://doi.org/10.1145/3543758.3543768

1 INTRODUCTION

Everyday Virtual Reality (VR) describes the shift from spacious, dedicated laboratory environments to confined, less controllable daily environments such as homes or transportation [10]. People have started to use head-mounted displays (HMDs) in a range of transportation means, from airplanes [47] to passenger cars [19, 26, 31, 36]. Thus, we expected that users might increasingly adopt immersive technology in the mobile context and bring their HMDs along the way to spend their travel time effectively for work or leisure. In such future mobility scenarios, prior studies listed a range of passenger activities from work in a virtual office [22] to relaxation at a virtual beach [24]. However, interruptions from the ever-changing surrounding real environment, such as a shared space in urban traffic, challenge users' feeling of presence in VR. These breaks in the presence [7] can be caused, for example, by onboarding passengers or incoming phone calls, which interrupt the activities users are doing in VR. Afterwards, it can be difficult for VR users to resume their previous relaxation state, or they might even drop out of the VR experience in emergencies.

Prior work by George et al. [11] explored seamless, bi-directional transitions across real and virtual environments by modifying visual, auditory, and haptic modalities to support simultaneous engagement in both realities. Additionally, in-car VR research revealed the challenge of the confined space around the user [32]. The limited in-car space constrains user movements in VR interaction. Here, our work is inspired by the concept of customizing the physical car interior to support VR adoption in future mobility [25]. This conceptual solution aligns with the notion of everyday physical proxies, with their passive haptics mapped to the virtual objects of similar shape and size, to facilitate everyday VR application scenarios within limited physical spaces [8, 15].

The guiding research question for this paper is: *How can we help in-car VR users recover from interruptions along the way and restore their feeling of presence?* Thus, we explore recovery strategies for users in such transitions from real-world interruptions back to their prior presence and relaxation in VR. First, we conducted automotive expert interviews (N=9) to understand the different types of interruptions from today's transportation and ideate recovery strategies when anticipating future scenarios of in-car calming VR applications [24, 36]. Based on the results, we decided on the interrupting incidents and the multi-sensory approaches for interruption notifications and recovery. To address the research question, we studied a new multi-modal transition approach through re-designing the car interior [8, 15, 25]. Specifically, we developed an interactive armrest for providing passive haptic sensations. By interacting with the armrest, users can leave traces of their haptic interaction on the physical armrest, visually reflected in the virtual environment in real-time. This interaction aims to remind users of their prior presence in VR and thus, foster their recovery of presence and consequent relaxation experience. In a lab study (N=30), we examined the influence of the interactive armrest on users' presence, relaxation, and recovery. We compared this multi-modal approach to two control conditions using the two single modalities: just visual traces in the virtual environment and just haptic traces on another baseline armrest.

The results from our study showed that the multi-modal experience lowered user awareness of the physical armrest more than the baseline conditions. When feeling virtual environments through the car-interior-based haptic display, users felt more relaxed and connected to the virtual environment. We discuss the implications for in-car VR research, including the potential of car-interior-based passive haptics, interruptions that are woven into VR, and simultaneous engagement across realities. The contribution of this paper is two-fold: (1) Exploring the potential of car-interior-based haptic displays with system details for supporting in-car VR recovery from interruptions. (2) Based on the empirical evidence, providing insights that indicate deploying multi-modal experience is beneficial for everyday in-car VR.

2 RELATED WORK

2.1 Less Controllable Real Environments in Everyday VR

Observing disruptions from the real environment (RE) in everyday VR can be necessary, such as quickly answering or making a phone call while using the HMD. These real-world interruptions are essential to users and different from the breaks in presence (BIPs) [7] caused by technical issues such as HMD latency in VR games. Investigating these breaks and consequent recovery phases, Chung and Gardner [7] found that recovery time was correlated with the overall presence, times of BIPs, and user characteristics. However, it is unclear whether these results will also hold for real-world interruptions in everyday VR, as it omits additional factors such as the importance level of the interruption that can influence the breaks and recovery. Others explored various approaches to support real-world awareness in VR, e.g., the presence of bystanders [12, 34] and auditory cues [29, 34]. George et al. [11] studied multi-modal strategies for seamless transitions between REs and virtual environments (VEs) by using the visual metaphor of a window into the other reality and considering other modalities of audio and haptics. Maintaining real-world awareness and feeling of presence in VEs is essential and challenging in everyday VR with diverse interruptions from ever-changing REs.

2.2 Mapping Real and Virtual Environments for In-Car VR

Prior work has investigated a variety of in-car VR activities such as gaming [16, 17, 19], productivity [21, 22], and relaxation [24, 36]. As a result, passengers can immerse themselves in all kinds of VEs, from a virtual office for work [22] to a virtual beach for relaxation [24], escaping from their traffic surroundings. However, this future mobility also faces challenges from REs, such as motion sickness from vehicle motion [6, 31] and limited room for interaction inside the car space [32]. While disturbed by these interruptions along the way, it can be difficult for VR users to maintain work or relax in immersive environments. Prior studies addressed the issue of motion sickness by coupling movements between RE and VE through visual cues [16, 31]. Thus, users can observe real-time visual traces of vehicle motion in VEs while playing games or watching videos, preventing sensory conflicts between vision and the vestibular system. Turning the confined in-car space into tangible user interfaces, Li et al. [25] envision a customized car interior mapped to virtual counterparts, supporting interactions that exploit embodiment and tangibility of physical artifacts in this seated-scale VR. Therefore, users can feel physical changes in the car interior while seeing virtual counterparts in VEs through this car-interior-based haptic display. However, research on this idea remains conceptual and lacks empirical evidence.

2.3 Everyday Physical Proxies for Passive Haptics

Early studies on the use of tangible user interfaces in VR show that they improve immersion and user experience [45]. Mapping sensory between REs and VEs further introduces realistic behavior in immersive virtual environments [41]. A range of solutions includes handheld devices [4, 13], wearables [1, 9], grounded devices [18, 33], and physical proxies [42, 43, 46]. However, it is questionable whether these solutions are applicable in an everyday environment irrespective of its constraints, such as physical limitations or social norms. For example, sensory VR [14] demonstrated a form of passive embodied interaction, namely feeling the sand underfoot, to recreate the sensory qualities of being in a virtual beach environment. However, it is unrealistic to transfer a bulky sandbox to a small in-car space, just to improve HMD use. Everyday VR scenarios instead require contextual and scalable strategies, embedding tangible user interfaces seamlessly into various user surroundings with dynamic spatial scales. For example, the everyday physical proxy [8, 15] approach leverages everyday objects from users' surroundings to provide multi-sensory feedback for coupled virtual objects of similar shape and size by directly touching the physical objects. We transferred this approach to the confined in-car space, exploring car-interior-based physical proxies.

3 DEVELOPING IN-CAR CALMING VR

To address our research question, we first conducted expert interviews to understand possible real-world interruption types and interaction modalities for notifications and recovery solutions. Then, based on the interview results and the prior work [8, 15, 25], we developed a car-interior-based passive haptic display to support users' recovery of presence after real-world interruptions during transit. We chose to use a deformable physical object inside the car, which is synchronized with the visual changes in the VE. This interactive car interior allowed the users to leave haptic traces on the car interior and see the mapped visual traces in the VE to recall their prior presence in VR activities.

3.1 Automotive Expert Interviews

Here, we present the connection between the results and our system design choice. We first conducted one-on-one interviews with nine automotive HCI experts (recruited from the ACM AutomotiveUI community) to understand interruptions in future mobility. We have presented some of the results of this interview in a workshop paper before[23], however, as they are non achievable we are here reusing some of the content.

Interruptions Inside	***Re-navigate for Food*** *(Mdn = 4)* While relaxing, you suddenly want to stop by your favorite restaurant on the way.	***Adjust Temperature*** *(Mdn = 4)* While relaxing, you want to adjust the air conditioner and lower the in-vehicle temperature.	***Low Fuel Warning*** *(Mdn = 6)* While relaxing, the system informs you the fuel level is under 20% and suggests you visit a gas station.	***Make Phone Call*** *(Mdn = 5)* While relaxing, the system reminds you to call your friends.	***Invite to VR*** *(Mdn = 2)* While relaxing, you want to share the view with your friends.
Interruptions Outside	***Re-navigate for Quickest Route*** *(Mdn = 4)* While relaxing, the system suggests a faster route to avoid traffic jams ahead.	***Road Priority*** *(Mdn = 4)* While relaxing, the system asks your decision when in conflict with the facing car.	***Point of Interest*** *(Mdn = 3)* While relaxing, the system notifies you of passing by a place that you liked on the map.	***Answer Phone Call*** *(Mdn = 6)* While relaxing, your friends call you.	***Onboarding Passenger*** *(Mdn = 5)* While relaxing, the system notifies you of an onboarding passenger.

Figure 2: The ten interruptions discussed in our expert interview are divided into two groups, *Interruptions Inside* (top) and *Interruptions Outside* (bottom), depending on whether their source is inside the car (e.g., user-triggered, vehicle state) or an external influence (e.g., system-triggered, traffic situation). Four of them (blue box) were selected for the user study based on the interview results. The experts' importance ratings were shown with median values.

We first showed our experts a calming beach clip from the off-the-shelf application Nature Treks VR[1], to demonstrate how HMD users could relax in VR. By studying interruptions in calming VR, we ensure high familiarity and low interactivity in the primary task (i.e., relax) as a comparable low cognition baseline across users. Based on an HMI framework for automated driving [3], we had prepared ten incidents that were triggered by different sources occurring from inside and outside the vehicle. Making a Phone Call, for example, is triggered by the user and hence from inside the car, while Answering a Phone Call is triggered by an external source and notified through the VR system. Figure 2 describes the median values of importance ratings for the ten interruptions.

In the interview, we asked our experts to rate incident importance levels on a scale of 1-7 (1=not at all, 7=very much) and comment on sensory strategies for the notification of interruptions (transitioning users from VE to RE) and the recovery of presence in VR activities (from RE back to VE). We analyzed the medians for the ratings and coded expert opinions on using multiple modalities in automotive interaction. Within our experts' ratings, we selected four incidents covering the most urgent (*Answer Phone Call*, *Mdn*=6), the least important (*Invite to VR*, *Mdn*=2), and mild (*Make Phone Call*; *Onboarding Passenger*, *Mdn*=5) interruptions. Testing these four interruptions ensured our system covered more extreme cases (considering the importance) but still focused on everyday cases, such as the phone call and the onboarding passenger. Considering the limited realism fidelity in our testing driving simulator, we discarded the vehicle-state-related incidents (Low Fuel Warning, Adjust Temperature) and traffic-situation-related incidents (Road Priority, Point of Interest) in the user study.

Our experts agreed to use visual and auditory stimuli for incident notification and support subsequent recovery during the transit. However, their opinions diverged on using haptic stimuli (e.g., vibration) for notification because this active haptics was considered relevant to emergencies in the car context, which might interrupt the relaxation experience in VR. Therefore, we implemented visual and auditory feedback rather than haptic stimuli to notify an incident. Regarding the following recovery phase, our experts did not have strong opinions for haptic stimuli during in-car VR without

[1]https://www.greenergames.net/, last visited July 5, 2022

Figure 3: Notification displays of interruptions: a) *Answer Phone Call*, b) *Onboarding Passenger*, c) *Make Phone Call*, and d) *Invite to VR*.

testing but found passive haptic stimuli more promising than active haptics. Thus, we developed an interaction using passive haptics through the car interior (e.g., direct touching) rather than active haptics to recover presence in VR.

3.2 VR Prototype Using Car-Interior-Based Passive Haptics

Our choice of virtual environment aligns with previous studies of calming VR applications for passengers based on landscapes with water [24, 36]. We created a dynamic virtual beach setting that includes flying birds, moving clouds, swinging palms, and ambient particles. For audio, we blended the sound of the waves with bird sounds in the virtual beach. We implemented this environment in Unity. Additionally, we implemented the above-mentioned four interruptions (see Figure 3). When receiving an incoming phone call, VR users can *Answer Phone Call* by swiping the slider to the right with the hand-held controller to start a video chat. When detecting an onboarding person on the way, the VR system will pop up a window to reality [11]. By swiping to the right using the controller, users can access a camera view of their real surroundings and the *Onboarding Passenger*. We implemented a calendar notification in VR to remind users to *Make Phone Call* during the trip. Likewise, they can start the call by using the controller. Finally, we implemented a system notification of *Invite to VR*, so that VR users can interact with their friends (3D avatars) in the VE with the controller. We placed these pop-up notifications in three horizontal displays or windows to REs as proposed in the prior work [11]. The UIs for *Make Phone Call* and *Answer Phone Call* were placed in the user's center view, while *Onboarding Passenger* placed on the right and *Invite to VR* on the left, both tilted 50° towards users for readability

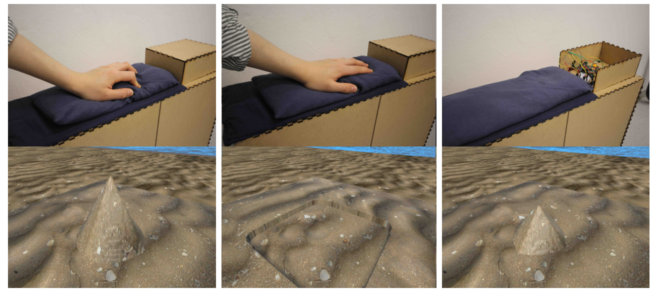

Figure 4: Our car-interior-based passive haptic display lets users feel and play with the sand while relaxing at a virtual beach during transit. Users can pile up (left) and push down (middle) the virtual sand. The images on the right show the user marks left on the interactive armrest and in the virtual sand.

(see Figure 1). We made all UIs translucent and played the same background music at a lower volume during interruptions.

To facilitate the recovery from these interruptions, we implemented the car-interior-based passive haptic display. In this study, we explored a deformable car region, the middle armrest in the rear seat. First, to create an immersive experience of relaxing at the virtual beach, we replicated the haptic sensation of playing with grains of sand in real life. We found that this sensation could be adequately provided by a cherry stone pillow on which users could rest their arm and palm. Furthermore, squeezing the cherry kernels in the cushion alludes to squeezing a stress ball to reduce anxiety and stress. Inside the pillowcase, we integrated an AMOTAPE elongation sensor tape[2] and a force-sensitive resistor (FSR) MD30-60. Both sensors were connected to an Arduino Uno microcontroller and powered via a laptop.

Two elongation sensor tapes were stitched into the pillowcase on the left and right, respectively. The resistance changes when the user squeezes or releases the pillow. During in-house testings, we established the threshold based on the default tightness of the sensor tape: left $value = 22$ and right $value = 5$. These values were dependent on their different default positions and stretching states. If either input value is higher than the threshold, the sand begins to pile up. If both input values are less than or equal to these threshold values, the sand pile in the virtual environment does not change. Likewise, we set two thresholds for the FSR recognizing when the user presses down on the pillow center: low $value = 0$ and high $value = 300$. The virtual environment remains unchanged when the input is less than or equal to the low threshold. If the value is higher than the low threshold and lower than or equal to the high threshold, the sand pile falls slowly. The sand pile quickly depletes if the value is above the high threshold.

As a support for the pillow, we built an armrest base using medium-density fibreboard (MDF). Figure 4 shows its haptic interaction design: While relaxing at the virtual beach, users can pile sand or push it down. When they pause interaction with the armrest due to interruptions, both shapes of the virtual sand pile and the physical armrest remain in their last states. Such interaction

[2]https://amohr.com/en/portfolio/resistive-strain-sensor/, last visited July 5, 2022

enables users to leave haptic cues on the cherry stone pillow while seeing the visual changes mapped at the virtual beach. These were designed as memory cues to help them recall and recover their prior presence and relaxation states in VR.

4 USER STUDY

We compared our system to two control conditions in a between-subject study, avoiding fatigue effects. Therefore, we designed two additional control conditions using only a single stimulus, the haptic (*Group H*) and visual (*Group V*), respectively. *Group H* uses the same cherry stone pillow but is detached from the interaction with the VE. Therefore, users can only leave haptic traces on the armrest without seeing changes in the virtual sand. For *Group V*, we built another baseline armrest using a foam cushion with little, ephemeral deformability but the same interactive setup inside the pillow for comparison. Thus, users can play with the armrest to see the changes in the virtual sand but can not leave haptic traces on the armrest. Both armrests were the same size and used the same pillowcase to ensure a similar tactile material sensation. In the experiment condition *Group HV* using both haptic and visual stimuli, users can leave haptic cues on the deformable armrest and synchronously see the mapped visual changes on the virtual beach. The audio stimuli were designed comparable for relaxation across groups to discard confounding factors. As a within-subject factor, the two types of interruptions (*Interruptions Inside* vs. *Interruptions Outside*) appeared in counterbalanced order in each group.

4.1 Apparatus

To simulate the mentioned virtual beach environment, we used an Oculus Rift S (Horizontal FOV= 88°±6.3°, Vertical FOV= 89°±7.5°, 2560×1440, $80Hz$) with integrated headphones and the right-hand controller as the input device to interact with the interruptions. To run the calming VR application, we connected the headset to a desktop PC with an Intel i7-6700K CPU with 16 GB DDR4 RAM, equipped with the graphics card NVIDIA GeForce GTX 1080 with 8 GB RAM.

The haptic displays differed across groups: i) *Group HV* used the mentioned interactive armrest ($35cm \times 15cm \times 3cm$, see Figure 4); ii) *Group H* used the same cherry stone pillow but detached from the visual changes. So the participants could only feel the tactile sensation from the armrest without seeing the mapped visual changes in the beach scenario; iii) *Group V* used the aforementioned baseline armrest ($35cm \times 15cm \times 1.5cm$). In the driving simulator, we covered the steering wheel, pedals, and the gear stick during the experiment to eliminate the sense of being a driver, as depicted in Figure 5. A video clip[3] of the rear-seat passenger view was played on the PC in the front display (43 inches, 3840×2160, $60Hz$) to let participants take on the role of a passenger.

4.2 Measures

To analyze the influences of the haptic display, we measured presence using the **presence curve** [27] and the **IPQ questionnaire** [40] after the VR experience outside the HMD. We combined a physiological measurement by inspecting **Electrocardiography (ECG)** **data** from a Polar H10 heart rate sensor, with subjective **relaxation ratings** on a 7-point Likert scale (1=extremely stressed, 7=extremely relaxed) asking "How relaxed do you feel now?" every 2.5 minutes to measure users' relaxation states during the VR experience inside the HMD. In addition, we recorded the **recovery time** needed to restore the pre-interruption rating of relaxation. Finally, we tracked **haptic input** before and after interruptions in a Unity log file.

[3]https://www.youtube.com/watch?v=kE2vLUfTAqY, last visited July 5, 2022

Figure 5: Our laboratory set-up consists of a driving simulator with a desktop PC, a display, and an Oculus Rift S headset (with a right-hand controller) connected to the desktop PC.

4.3 Procedure

When participants arrived at the lab, they observed a local hygiene concept. Then, after being introduced to the background of in-car calming VR, they filled out a demographic questionnaire including their prior experience with VR and passenger trips. The experimenter helped the participant put on the heart rate chest strap and the headset in a trial round to familiarize users with the controller usage (e.g., in-VR relaxation ratings) and the armrest (e.g., pile and push down sand). Next, in the official round, the experimenter played the passenger-view video on the front display for one minute to expose participants to the transportation context and let them mentally slip into the role of a passenger. The video clip was looped at a reduced volume to simulate the traffic sound for the whole study. The experimenter then instructed the participant to put on the headset and relax at the virtual beach for five minutes. During relaxation, participants interacted with the armrest while feeling haptic changes and/or seeing changes in the virtual sand depending on the assigned group. In between, in-VR ratings measured their relaxation states every 2.5 minutes. This baseline relaxation was followed by the first round of interruptions lasting around 2.5 minutes. The system notified the participant to take action on a pair of incidents, *Interruptions Inside* or *Interruptions Outside* depending on the assigned order. During interruptions, participants could interact by swiping on the slider to the right via the controller in all groups. Immediately after the interruptions, the in-VR rating appeared again, acquiring relaxation states, and the ECG data was recorded. Meanwhile, participants were asked to resume the relaxation phase by feeling and/or seeing the traces left before in the

Table 1: Descriptive Statistics of the relaxation state before and after the interruptions including physiological ECG data and subject ratings with mean (*M*) and standard deviation (*SD*), with statistic testing results.

	Pre-Interruption						Post-Interruption					
	Group H		*Group HV*		*Group V*		*Group H*		*Group HV*		*Group V*	
	M	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**
HR (BPM)	83.55	11.00	83.46	8.93	81.95	12.32	80.46	9.75	84.54	8.56	79.96	10.83
	$F(2, 25) = 0.063$, $p = .939$, $\eta^2 = 0.005$						$F(2, 25) = 0.606$, $p = .553$, $\eta^2 = 0.046$					
RR (ms)	728.60	88.54	726.02	75.55	747.24	114.20	755.27	88.18	716.02	70.44	761.06	107.67
	$F(2, 25) = 0.138$, $p = .0872$, $\eta^2 = 0.011$						$F(2, 25) = 0.675$, $p = .518$, $\eta^2 = 0.051$					
Relaxation Ratings	6.3	0.82	5.8	1.23	6.0	0.82	5.2	1.32	5.3	1.42	5.4	0.84
	$F(2, 27) = 0.665$, $p = .522$, $\eta^2 = 0.047$						$F(2, 27) = 0.067$, $p = .935$, $\eta^2 = 0.005$					

assigned group. The second relaxation phase continued until the participant had recovered to the baseline relaxation state before the interruptions. Therefore, the second phase had a different duration (i.e., multiples of 2.5 minutes such as 0, 2.5, or 5 minutes) depending on individual recovery speed. By personalizing recovery duration, we ensured that the participants restored their prior self-report relaxation states. Then, another round of interruptions of the other respective type and the third relaxation phase repeated. The virtual beach scene was present as the background environment throughout the VR experience. The study was completed with the presence curve task and questionnaire outside the HMD for participants retrospecting on the VR experience and a final interview asking for their opinions and comments on the implemented haptic display and virtual scenes. The study took around 45 to 60 minutes in total for each group.

4.4 Participants

We invited 30 participants (14 female, 16 male) aged between 20 and 33 years ($M = 23.1, SD = 2.78$) to our driving simulator lab. More than half of the participants (n=22) had experienced VR HMDs before. All of them had traveled as car passengers before, most on a monthly (n=13) basis. The majority travels less than 10,000 km per year (n=19), spending 30-60 minutes on average per journey (n=15), and engaging in entertainment activities (n=24). We recruited the participants via the mailing list of our institute and compensated them with 10€ for their participation. Each participant confirmed their consent according to GDPR.

5 RESULTS

We used one-way independent ANOVA tests to examine changes in presence, relaxation state, and haptic input across three groups and the mixed factor align-and-rank ANOVA [48] for non-parametric data. Dependent t-tests were used for verifying differences between the two types of interruptions and Wilcoxon's signed-rank tests for non-parametric data. We used Shapiro-Wilk tests as a normality check. Statistical significance is reported for $p \leq .05$.

5.1 Interruption and Recovery

5.1.1 Overall Impact of Interruptions. By comparing the final relaxation state to the baseline, we quantified the overall impact of the interruptions across groups by examining the difference between the pre- and post-interruption ECG data and ratings. We excluded the incomplete ECG data of two participants for the following analysis (see Table 1). On average, our participants experienced increased heart rate along with decreased RR intervals only in *Group HV* but lowered their subjective relaxation ratings in all three groups. We found no significant differences in these relaxation measurements.

When examining the overall interruption impact on presence, we focused on the moments immediately before the first interruption and after the last interruption. Specifically, we clustered the identified trends drawn by our participants in the presence curve [27]: a) Phase of Constant Presence, the curve keeps horizontal throughout the selected phase; b) Phase of Raising Presence, the curve shows an increase in the feeling of being present in the VE; and c) Phase of Dropping Presence, the curve shows a decrease of presence, namely feeling more in the RE. Consistent with the decrease of relaxation in all groups, we found that the interruptions overall diminished presence for 7 out of 10 subjects in *Group HV*, 6/10 in *Group H*, and 7/10 in *Group V* (see Figure 6 left).

5.1.2 Overall Presence, Recovery of Presence and Relaxation, and Haptic Input. The IPQ overall presence measured after the VR experience showed no significant differences across groups. On average all the groups reported a moderate level of presence (see Table 2).

After the two rounds of interruptions, eleven participants transitioned back only once, either after *Interruptions Inside* (n=2) or *Interruptions Outside* (n=9), and ten participants skipped both recovery phases due to their identical in-VR relaxation ratings before and after each round of interruption. The remaining nine participants transitioned back twice to the virtual beach and continued to recover their presence and relaxation. Out of these nine participants, two participants in *Group HV* experienced both recoveries with an average duration of 3.8 minutes ($SD = 1.44$) and a mean HR of 74.30 BPM ($SD = 7.4$). This recovery was comparable with the five participants *Group H* and the two in *Group V*. We found no significant differences in the duration and HR data across groups (see Table 2). Irrespective of interruption types, we clustered the presence curve in the middle phase of recovery between the first and the last interruptions (see Figure 6 right). The results unveiled a dominant Phase of Raising Presence in all groups (*Group HV*: 7/10, *Group H*: 5/10, and *Group V*: 8/10).

Moreover, we analyzed our participants' interaction with the two implemented armrests in *Group HV* and *Group V*. The log

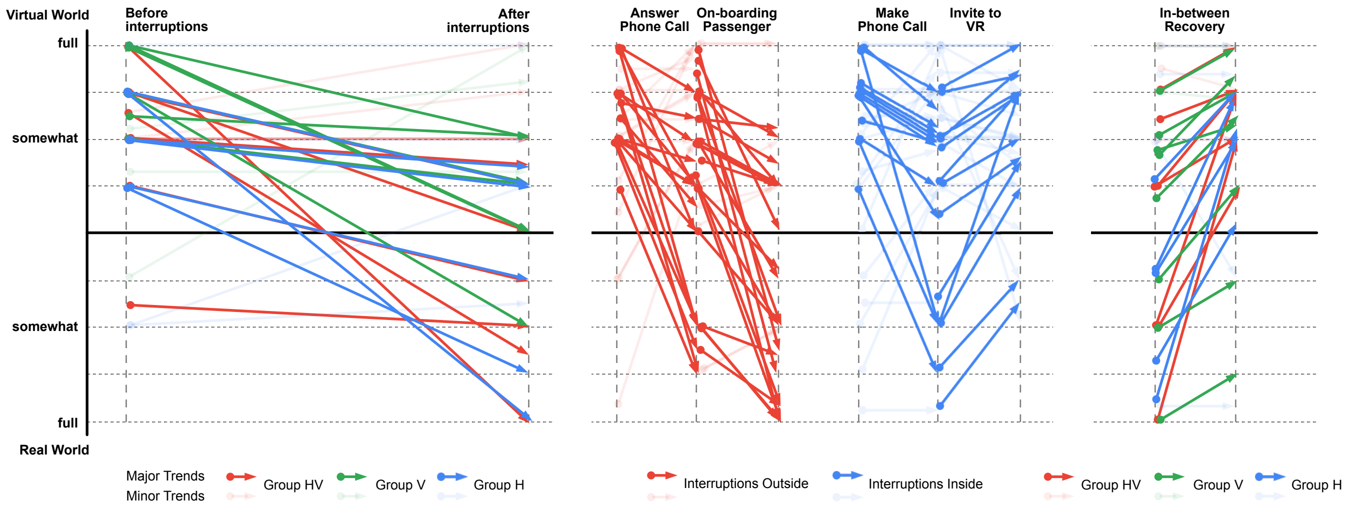

Figure 6: An overview of the identified dominant trends of presence across overall impact of interruptions (left), different types of interruptions (middle), and the in-between recovery phase (right). For details of the method see Mai et al. [27]

Table 2: Means and standard deviation of IPQ presence (overall score), recovery time (minutes) and HR (BPM), and haptic input: pile up and push down (times per minute) across groups, with statistic testing results.

Group	IPQ Presence		Recovery				Haptic Input			
			Time		HR		Pile Up		Push Down	
	M	SD	M	SD	M	SD	M	SD	M	SD
Group H	4.57	1.01	4.8	2.49	81.31	12.8	n/a		n/a	
Group HV	4.62	0.93	3.8	1.44	74.30	7.4	9.11	7.59	16.7	13.6
Group V	4.39	0.94	3.8	2.5	78.95	15.16	10.7	7.46	12.2	11.1
	$F(2,27) = 0.154$ $p = .858, \eta^2 = 0.011$		$F(2,6) = 0.57$ $p = .593, \eta^2 = 0.16$		$F(2,6) = 0.19$ $p = .832, \eta^2 = 0.059$		$U = 37$ $p = .829$		$U = 53$ $p = .274$	

file showed that the participants piled up the sand sightly less and pushed down more on average in *Group HV* than *Group V*. However, we found no significant differences in these haptic inputs between the test and control armrests (see Table 2). Our participants did not report any observable latency in the synchronization between the haptic display and visual stimuli in these two groups, which aligns with the calibration result in our dry run.

5.1.3 Impact of Interruptions Inside vs. Outside. Regarding the impact of the different interruption types on presence, we focused on the phases of each incident during the entire VR experience in each group. Figure 6 middle shows an overview of the presence curves differing across four interrupting incidents independent of the group. Specifically, we found a variety of dominant trends (the highest count of the Phase of Constant/Raising/Dropping Presence within each condition): more than half of our participants (n=23) experienced the Phase of Dropping Presence in *Onboarding Passenger*. The same experience was voiced by the majority in *Answer Phone Call* (n=17) and in *Make Phone Call* (n=13), while a noticeable Phase of Raising Presence (n=13) was found in *Invite to VR*. Along with the drop in presence in *Interruptions Outside*, a Wilcoxon’s signed-rank test showed a significantly stronger impact of *Interruptions Outside* on the relaxation ratings than the *Interruptions Inside*, $W = 20, p = .021$ (see Figure 7 left).

5.2 Interview Feedback

In the final interview, we asked participants to reflect on their VR experience and haptic display usage. Two experimenters developed a series of themes based on the original notes as demonstrated by Braun and Clarke [5]. The resulting themes are presented below with direct quotes identified with user IDs.

5.2.1 Relaxation, Connectedness, and Awareness. Some participants appreciated the interactive armrest design in *Group HV*, as with this (passive) haptic display they *“felt relaxed at the virtual beach and even when reacting to the interruptions” (P12)*. In contrast, the control armrest in *Group V* was criticised for *“no relaxing effect when pressing” (P19)*. Some participants desired *“another material for more fun” (P20)* (see Figure 8 left). In addition, the synchronization between the haptic display and the changes in the virtual environment in *Group HV*, i.e., feeling and seeing the sand variation, was well received by our participants. They found the interactive

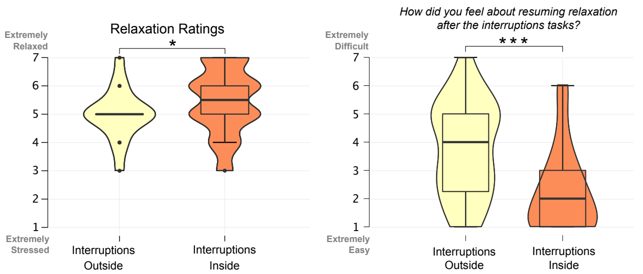

Figure 7: In-VR relaxation ratings (left) and post-experiment ratings of resuming difficulty (right) between the two interruption types. $***$ denotes significance at $p \leq .001$. $**$ denotes significance at $p \leq .01$. $*$ denotes significance at $p \leq .05$.

armrest enriched presence and realism, such as *"when touching something, I felt being inside the virtual scene" (P2)* and *"the interactive sand makes the whole scene feeling more real" (P12)*. They also voiced an enhanced connectedness to the virtual environment, e.g., by *"realizing that I can control the sand made me feel immersed" (P9)*, and saying that *"directly manipulating the virtual environment made me feel related to it" (P26)*. Mann-Whitney U tests showed a significantly stronger feeling of connectedness to the virtual environment in *Group HV* than *Group H* when using the same physical armrest, $U = 23.5, p = .044, d = -0.53$ (see Figure 8 middle). In comparison, the detached interaction in *Group V*, i.e., seeing but not feeling the sand variation, was found *"inconsistent with the real world" (P19)*. Similarly, the non-interactive armrest in *Group H*, i.e., feeling but not seeing the sand variation, sharpened the awareness of the armrest and some participants *"felt disconnected to the beach by touching the armrest" (P13)*. Meanwhile, the participants in *Group HV* gradually became unaware of the interactive armrest *"after knowing how it works" (P8)* and *"almost forgot the hand was on an armrest" (P5)*. Instead, the interaction *"was just felt like grabbing sand and watching its changes" (P26)*, or *"a natural behavior" (P2)*. The mixed factor align-and-rank ANOVA showed a significant effect of the group, $F(2, 27) = 5.954, p = .007$. Post hoc tests showed *Group HV* introduced significantly lower awareness of the armrest than *Group V* (p=.006), see Figure 8 right.

In summary, the *Group HV* participants felt more relaxed, related to the virtual environment, and less aware of the armrest during the rear-seat VR experience, compared to the *Group H* and V (see Figure 8).

5.2.2 Interruption and Recovery. When asked about the differences between the two interruption types, our participants felt strongly disrupted after the *Onboarding Passenger* due to the lack of *"seeing the person" (P18)* and *"social interaction like greetings" (P9)* in VR. The *Interruptions Inside*, however, due to the avatar voice and body representations in *Make Phone Call* and *Invite to VR*, was rather perceived as a part of the VE. Thus, our participants *"did not have the clues of the real world" (P24)*, neither bothered to *"transit from the real world to the virtual world" (P2)*, but felt *"more relaxed" (P8)* and *"easier to recover" (P6)*. Furthermore, some pointed out that the *Interruptions Inside* felt like spontaneous decisions to pause the relaxation *"instead of someone interrupting you" (P10)*, which

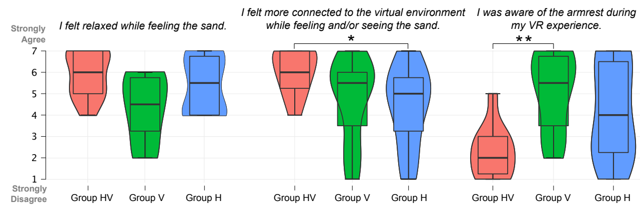

Figure 8: Evaluation of the relaxation (left), connectedness (middle), and awareness (right) of different armrests. $* * *$ denotes significance at $p \leq .001$. $**$ denotes significance at $p \leq .01$. $*$ denotes significance at $p \leq .05$.

felt less disturbing given the implemented *"reminder design" (P17)*. Wilcoxon's signed-rank tests showed a significantly lower difficulty in resuming calming VR experience after *Interruptions Inside* than *Interruptions Outside*, $W = 227.5, p = .001, r = 0.798$ (see Figure 7 right).

6 DISCUSSION

6.1 Synchronous Multi-Modal VR Minimizes Gaps between Two Realities

Unlike prior work [14], our results did not confirm higher presence and relaxation in the multi-sensory VR experience in *Group HV* compared to the uni-modality interaction in *Group H* and *Group V*. In contrast, the ECG data indicated a less relaxed state or higher arousal on average in multi-modal experiences, i.e., higher heart rate, lower HRV, and lower subjective ratings of relaxation, in the implemented virtual beach environment. We speculate that the higher arousal could be caused by more frequent physical activity on average in *Group HV*, i.e., interacting more often with the armrest when feeling more present in the beach scenario may have caused the higher heart rate and lower relaxation ratings. However, we recommend further investigating these indicators using more sensitive physiological measurements to capture relaxation states in VR. Nonetheless, post-experiment ratings revealed a stronger feeling of connectedness to the VE when seeing and feeling sand traces synchronously in multi-modal interaction. Additionally, the implemented interactive armrest introduced the lowest awareness of the armrest than the un-deformable baseline armrest.

6.2 External Interruptions Introduce Stronger Effects

We tested two interruption types based on the expert interview results. One is triggered by users from inside the vehicle and the other by a source from outside the vehicle. The results showed a significantly stronger impact of *Interruptions Outside* on subjective relaxation ratings than *Interruptions Inside*, while the physiological impact was comparable. The qualitative data of the presence curve and subjective comments also reflected this stronger impact of the external interruptions, especially in the dominant Phase of Dropping Presence, when our participants encountered the *Onboarding Passenger* but without seeing or interacting with the person. In comparison, we found that most participants experienced the Phase of Raising Presence in *Invite to VR* with the precluded surroundings and extra efforts to transit between the two realities. Together, we conclude that from real-world interruptions back to relaxation in VR, interruptions triggered by external sources from outside the car influence recovery more negatively than the user-triggered ones from inside the car.

6.3 Limitations

In the study, we used a static testing environment. Therefore, our results might change if participants were exposed to interruptions in the wild, such as meeting a real person getting on board or feeling motion-sick in a moving car. These incidents can be more distracting than only viewing the next passenger in the current picture-in-picture video clip while the car is "parked". We also reflect on the controlled severity and limited types of the implemented interruptions, which are mild and expected, compared to severe and unexpected ones such as a car accident or sudden shouts from pedestrians. However, in these long-tail extreme cases, the users might take off the headset and abort the experience with no need to transition back to the VE and neither recovery, which explains our decision to focus on mild everyday interruptions. Finally, we reflect on our prototype, using cherry stone pillows, which might affect the feeling of presence compared to interacting with real sandbags. Future studies could test different materials and deformability of in-car physical proxies.

7 IMPLICATIONS FOR EVERYDAY IN-CAR VR

7.1 Re-design the Car Interior into Physical Proxies for Connected Experience

Our concept of a car-interior-based passive haptic display, in which the tangible interaction (pile up and push down) synchronized with the visual changes at the virtual beach, was preferred by our participants. They found that our prototype helped them *"relax" (P12)* and *"immerse" (P9)* in the VE while becoming *"unaware of the armrest" (P5)*, which created a *"more real" (P12)* and *"related" (P26)* experience at the beach. Based on the idea of designing the car interior to support passenger use of HMDs [21, 22], we built the armrest to provide passive haptics for in-car calming VR experiences. We found promising effects on subjective feelings of connectedness and less awareness of surrounding objects. It is worth investigating other application scenarios and VEs, such as passenger productivity and entertainment, using car-interior-based passive haptic display or general design strategies, connecting REs and VEs through anchors or memory cues [2] across modalities. For example, the passive haptics from the armrest can be mapped to the virtual counterparts in a virtual office like a deformable stress ball on the desk. Furthermore, changing the passenger seat position in real life as kinesthetic cues might be comparable to this passive haptic concept. Starting from this single RE and VE and single intensity level of passive haptics, we call for future research deploying passive haptics based on various in-car spaces and immersive virtual environments for diverse passenger activities. Likewise, future studies can explore the design of multiple intensity levels of haptic sensation, e.g., according to the importance of interruptions.

7.2 Weave Interruptions into Virtual Environments for Seamless Transition

In total, eleven participants skipped both transition phases as they did not lower their relaxation ratings after both interruptions, as some *"did not feel pulled over to the real world" (P12, P8)* during the interruptions in this lab study. Others explained that the interruptions felt more like *"watching a video of a friend which belonged to the beach experience" (P13, P15)* and *"interact with the person" (P17)*, which was even *"relaxing" (P8, P13)* to some of them. Others additionally liked how the interruptions and the virtual beach scenario were integrated by its design, e.g., *"the color, UI of notification is well merged into the scene" (P11)*. This showed the potential of integrating certain types of interruptions (e.g., mild and less urgent incidents) into immersive virtual environments without interrupting the primary task. However, we need to verify such design of interruptions in a higher fidelity testing environment, for example, by testing an actual onboarding passenger in the wild. Moreover, future studies could investigate design factors of notifications such as the position and alignment [38, 39] to weave real-world interruptions into VR.

7.3 Design Multi-Modal Interaction for Simultaneous Engagement in both Realities

Our multi-sensory VR transition concept diminished mismatches between the real and virtual world through lower awareness of the surrounding physical constraints and a stronger feeling of connectedness to the VE. Based on the preliminary data analysis, we speculate that the criteria of designing a "good" everyday mobile VR application will be beyond the concept of presence in a virtual environment only, but rather the simultaneous engagement in both realities [11]. To bridge the physical and virtual environments in the car and other transportation, future work can systematically examine such mappings, across interaction modalities (visual, audio, and haptic) [20, 30, 35] and presentations (literal, symbolic, and metaphoric) [2, 24, 28]. These various mappings across REs and VEs can offer multi-modal anchors and memory cues that enhance user connectedness to the VE and support effortless transitions between their primary activities and interruptions.

8 CONCLUSION

Our work explored the multi-modal interaction design for supporting in-car VR recovery from interruptions. Anticipating that VR HMDs might become widespread devices, we approached this less controllable environment by testing a subset of frequent but expected interruptions, two triggered from inside and two from outside the car, in a lab study (N=30). We developed an interactive armrest as a passive haptic display in mobile VR interaction to foster the transition between RE and VE. The concept was tested with mapped calming experiences (i.e., feeling and seeing the sand) at the virtual beach. Furthermore, we enabled VR users to change the virtual environment and leave their marks through our passive haptic display. We found this multi-modal interaction to lower user awareness of the physical armrest and increase their connectedness to the VE. Compared to research in RE [37, 44], this indicates the potential of creating more meaningful relationships and social connectedness between users and the VE. Accordingly, we see the effect of multi-modal traces of use as a promising future research direction in VR. Moreover, the implemented *Interruptions Outside* had a more negative impact on recovery than the *Interruptions Inside*. Based on these results, we discussed implications for future in-car VR interaction, including car-interior-based passive haptic displays, interruption integration, and simultaneous engagement in both realities in everyday mobile VR.

ACKNOWLEDGMENTS

We thank our study participants for their time and effort, and our anonymous reviewers for their constructive and insightful feedback. J.L.'s contributions were funded by the China Scholarship Council (CSC), grant number 201908080094.

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