VRySmart: a Framework for Embedding Smart Devices in Virtual Reality

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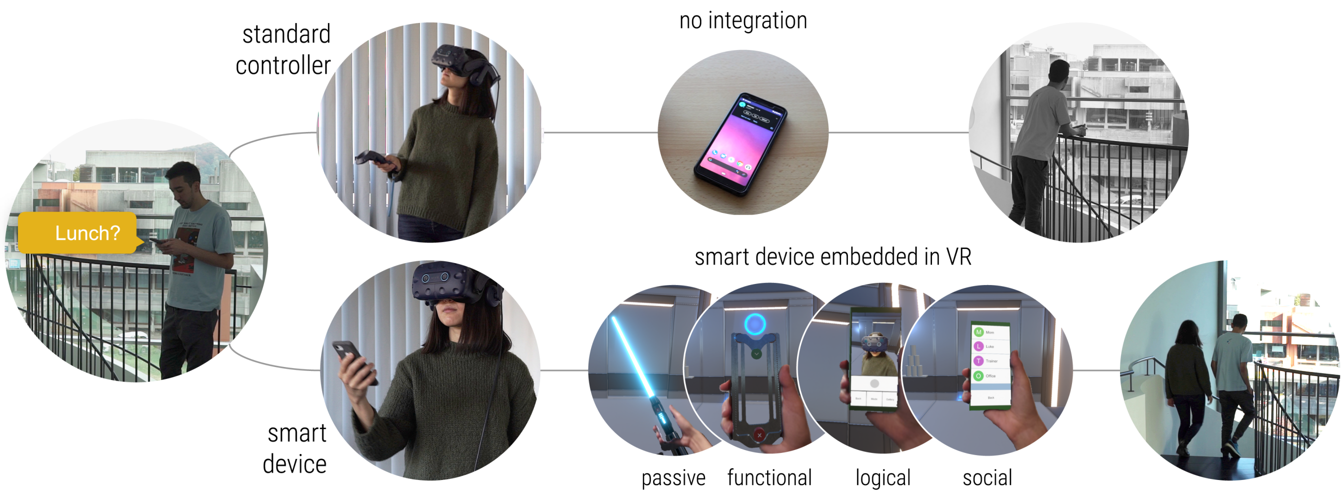

Figure 1: *VRySmart* is a framework for embedding smart devices in virtual reality (VR). In contrast to dedicated VR controllers, smart devices, such as personal smartphones, allow users to remain connected across realities while leveraging a familiar interface. Additionally, smart devices can provide haptic feedback and add novel functionality to virtual environments. With our framework, input and output sensors of smart devices can be extended to the virtual world, e.g., for creating mixed reality photographs using the camera.

ABSTRACT

As immersive virtual experiences find their way into our living room entertainment, they are becoming part of our daily technological consumption. However, state-of-the-art virtual reality (VR) remains disconnected from other digital devices in our environment, such as smartphones or tablets. As context switches between acting in the virtual environment and resolving external notifications negatively influence immersion, we look towards integrating smart devices into virtual experiences. To this aim, we present the *VRySmart* framework. Through either optical marker tracking or simultaneous localization and mapping (SLAM), embedded smart devices can be used as VR controllers with different levels of integration while their content is incorporated into the virtual context to support the plausibility of the illusion. To investigate user impressions, we conducted a study ($N = 10$) where participants used a smartphone in four different virtual scenarios. Participants positively assessed smart device usage in VR. We conclude by framing implications for future work.

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CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; **Smartphones**; **User studies**; *Haptic devices.*

KEYWORDS

smart devices, virtual reality, haptic feedback, framework.

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1 INTRODUCTION

Virtual Reality (VR) is slowly but surely integrating itself into our everyday technology stack. While immersed in a virtual environment (VE), users are able to experience exciting, artificially generated worlds in a convincing manner. However, state-of-the-art VR remains disconnected from other commonly used technology. As head-mounted displays (HMDs) obscure the real world, interacting with smart devices, such as smartphones or tablets, while maintaining the plausibility of the illusion becomes challenging.

Traditionally, smart devices use auditory or vibrotactile notifications to inform a user about outside events, such as incoming messages or voice calls. In order to respond to these events, users are required to take off their headset to locate and interact with the device in question. These context switches negatively influence the user's experience and break the illusion presented to them [10, 35].

To build more fluent interactions, previous work has laid the foundation for connecting smart devices in the real world to the virtual environment. On a functional level, smart devices have successfully been used as controllers in VR for tasks such as navigation and selection [8], sketching [11], or typing [20]. Moreover, Daiber et al. [3] recently proposed to leverage everyday objects, including smart devices, for various purposes in VR, such as for providing both passive or active haptic feedback. Previous research also explored logical integration of smart devices in VR applications. As an example, the *Immersive Notification Framework* by Zenner et al. [35] aims to integrate text messages on a smartphone into a virtual environment in a plausible and immersive manner. This contextual integration of notifications has been shown to affect reaction time, urgency, and understandability [10].

To advance this line of research even further, we present *VRySmart*, a framework for integrating smart devices, such as smartphones or tablets, into virtual environments, see Figure 1. The framework consists of two components, i.e., a main VR application and a smart device app, see Figure 2. While the VR component coordinates smart device representations in the virtual environment and provides visual segmentation algorithms, the smart device app provides supporting tracking methods, and communicates sensor events from the device back to the VR component. Built in Unity, *VRySmart* is able to track devices using either visual tracking, device-centric tracking, or through a combination of both. Using visual tracking, each smart device displays a dynamic set of fiducial markers which is captured by cameras integrated into or placed onto the HMD. Using the device-centric approach, each smart device uses *simultaneous localization and mapping* (SLAM) to capture its own coordinates which are converted to the shared virtual coordinate system. With our framework, a designer is able to create immersive experiences using available smart devices without the need for additional tracking methods. The designer is free to choose the virtual representation of each device operated by the user, while each device's sensors and actuators can be connected to the virtual experience to add both input and output mechanisms.

To showcase our *VRySmart* framework, we built a virtual experience where the virtual representation of a smartphone could be altered to evaluate four different scenarios. Each scenario provided a different level of integration to realize varying use cases for integrating smart devices in virtual settings. While in one scenario, the smartphone was tracked and used as a passive haptic proxy object [16, 22, 23] representing a virtual lightsaber (passive integration), the phone's on-board actuators and touchpad were used to simulate a futuristic catapult with vibrotactile feedback in the second scenario (functional integration). Additionally, the third scenario took advantage of the smartphone to let users take photos in VR and mixed reality selfies while immersed (logic integration), and the fourth scenario demonstrated how the phone can facilitate social communication with a simulated messenger app (social integration). To investigate initial user impressions of incorporating smart devices in VR, we performed a user study consisting of an exploratory think-aloud phase, followed by a semi-structured interview. From our results, we see that users were pleasantly surprised by using a smart device in a virtual environment. The pre-existing knowledge users have with regards to interacting with their own smart devices made them feel as if acting in the virtual environment was a logical next step. Here we see that users expect existing affordances and knowledge to be transported to the virtual experience. Furthermore, users provided example scenarios and applications they would value and underlined technological limitations which affected their experience.

2 RELATED WORK

In recent years, smart devices have found their way into virtual worlds with varying degrees of integration. Firstly, due to their network capabilities, large touch surface and integrated sensors, smart devices provide an opportunity for embedding them into virtual environments, e.g., as handheld controllers. Moreover, modern devices have a diverse set of modules, e.g., cameras, fingerprint sensors, proximity sensors, and standard input and output components such as speakers and microphones, which have the potential to provide additional functionality to virtual settings. Lastly, as smartphones are commonly used for social communication, embedding smart devices into VR can help immersed users to remain connected to the outside world. We provide a brief overview of work related to these advancements.

Past research has introduced smart devices as virtual controllers. In the simplest case, a smart device can be used as an input device without any visual representation. Examples of this include the work of Steed and Julier [30] as well as Liang et al. [19] where touchscreens are used as input devices for virtual navigation. Moreover, data from phones' inertial measurement units (IMUs) has been

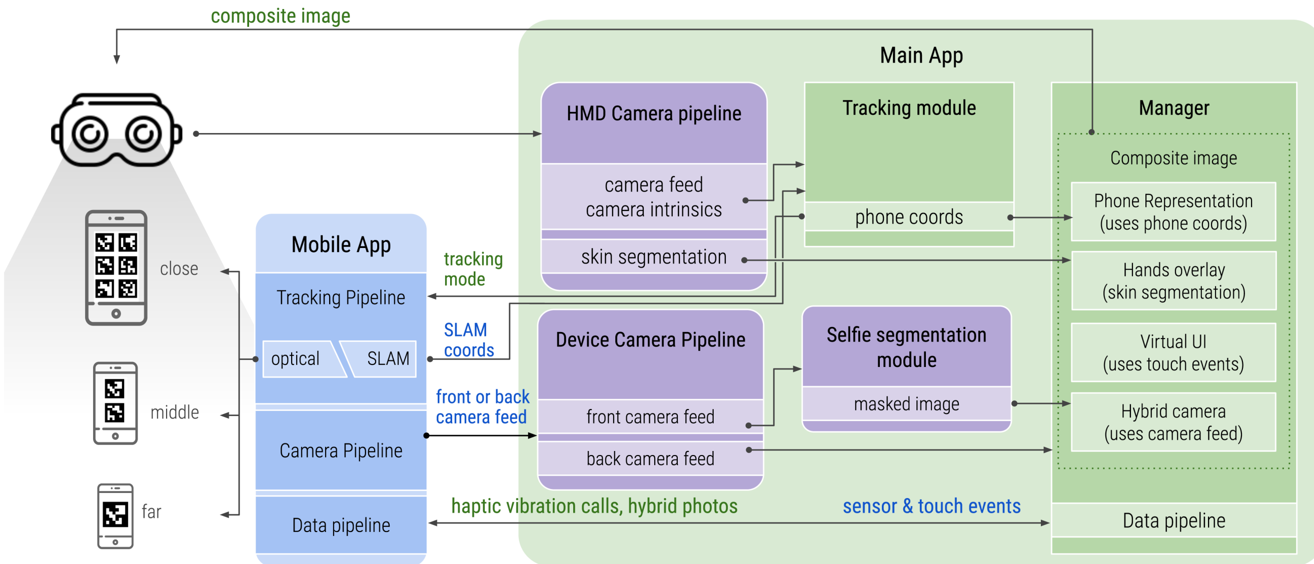

Figure 2: Conceptual representation of the workflow of the framework.

used to control a cursor using pointing gestures [15, 17]. Fully, externally tracked and visualised devices allow for more sophisticated interactions in VR. Wilkes et al. [33] explore how embedded multi-touch mobile devices can be used for 3D object manipulation, while Boustila et al. [2] address the usage of a smart device for text typing. Similarly, Savino uses a fully embedded smartphone to aid in navigation tasks in virtual environments [25]. Fully-featured embedding of a smartphone in VR is described by Zhang et al. [36]. Here, the smartphone attached is to a VR controller while its contents is fully mirrored to its virtual representation.

As smart devices grow to be smarter, their integrated and sophisticated sensors can be leveraged to improve interaction in VR. The ability to detect (and visualize) fingers hovering over the display allows for more precise input instead of the conventional *aim and shoot* method [18]. Furthermore, the frontal camera of a smartphone can be used to integrate a visualization of users' hands in VR while interacting with the touchscreen [20]. Using the frontal camera, a visual marker attached to the HMD can be tracked, acquiring the phone's position relative to the headset [8, 21]. Using SLAM via the back camera allows smartphones to employ an inside-out tracking, positioning themselves in the virtual environment [14]. In commercially available systems, the recently released HTC Vive Flow VR-system uses a smartphone as a main controller as it does not come with any dedicated controllers[1]. Here, the virtual phone rotates around a fixed pivot point that approximates the position of the elbow. This provides the illusion of tracking in space.

While the aforementioned works focused on interaction techniques, past research has addressed the connection of users in VR to the outside world with the help of smart devices. When putting on a VR headset and immersing temselves in the VE, users are disconnected from the real, physical world. To overcome this barrier, different approaches have been investigated to establish a connection to bystanders in the same room or to people at a distance. The configurable VR-HMD system by Isamu et al. [9] includes a smartphone as a periphery aware display for the immersed user and can be reused as an external display for a bystander when detached from the HMD. In earlier work by Gugenheimer et al. [13], authors use mobile touch displays mounted around a VR-HMD to engage bystanders by displaying the virtual content to the outer world and serving as an additional interaction layer. In subsequent work [12], a similar mobile display is attached to a controller given to a bystander. The display along with the floor projection places the non-HMD user inside the virtual context and makes them part of the experience. Similarly, a tablet as a tool for synchronous asymmetrical interaction is presented in the *TransceiVR* project, where collocated and remote users can annotate content of the virtual scene [31]. To further include people and events that are spatially divided from the VR user, Ghosh et al. [10] explore ways of incorporating digital notifications in VR. They propose design recommendations through an analysis of user preferences and notification importance. While Rzayev et al. [24] focus on how users perceive such notifications based on their placement and the virtual task, Zenner et al. [35] presented an adaptive framework for connecting immersed users with the real world events using adaptive notifications. In their work, contextual integration is added to the experience to ensure the plausibility of the illusion is maintained.

While some features and technologies of our proposed framework have been presented in the past, we contribute an approach in a single framework. Additionally, we provide empirical results gained from a user study using different scenarios implemented using our framework.

[1]Vive Flow - https://www.vive.com/us/product/vive-flow/overview/.

3 VRySMART FRAMEWORK

To investigate the interactive and connected use of smart devices in virtual spaces, we created the *VRySmart* framework.

Overview. Our framework consists of two separate implementations, i.e., a VR component and a smart device component. While the VR application takes care of coordinating the smart device representations in the virtual environment and visual segmentation algorithms, the smart device app provides supporting tracking methods, and communicates sensor events from the device back to the VR component. Both components are built on top of Unity 2019.4 and is accessible online[2]. As the project can be built for different operating systems, a wide range of smart devices is supported.

Tracking. To track smart devices, currently our framework provides two methods: optical marker tracking displayed on the smart device and SLAM-based tracking performed by the smart device. Using on-screen markers, the VR component visually captures each device's orientation and relative position to coordinate their visual representations. Depending on the form factor and resolution of the tracked device, the size and amount of markers can be adjusted to ensure stable tracking at varying distances despite occlusion during touch interaction. While currently done manually, a future extension is looking at dynamic marker adaptation based on estimated distance from the capturing device. Capturing markers is done using a camera mounted onto or built into the head-mounted display. Using SLAM, each smart device captures its own position within the real environment and communicates the resolved coordinates to the VR component. To consolidate the different coordinate spaces, both approaches require a calibration. For the optical tracking approach, only the offset between the capturing device and the HMD needs to be entered. For the SLAM-based approach, the different coordinate spaces need to be consolidated in a manual calibration step to calculate each offset. Here, the user is asked to physically align the smart device with a virtual representation in different locations.

Interaction. As the user physically interacts with the smart device, its virtual, visual representation can be dynamically adjusted. Similar to standard controller interaction, all events are communicated to the VR component. A skin segmentation algorithm creates a separate layer of the user's hands from the image of the HMD camera. By overlaying this image onto the visible composition through the HMD, the user is able to efficiently interact with the touch screen. Additionally, an interface is provided to access the camera stream of each camera on the smart device. Combined with an open source human segmentation neural network[3], the user is able to take pictures of bystanders projected in the virtual environment and "selfies" using the front-facing camera.

4 USER STUDY

To evaluate our framework and receive initial feedback, we performed a user study in our lab. The study consisted of a think-aloud exploration process with open-ended tasks, followed by a semi-structured interview session. Approval was obtained from the Ethical Review Board of the Department of Computer Science at Saarland University (No. 21-10-1).

[2]VRySmart Framework - https://github.com/AkhmadMax/VRySmart
[3]SelfieSegmentationBarracuda - https://github.com/creativeIKEP/SelfieSegmentationBarracuda

4.1 Apparatus

Using the *VRySmart* framework, we created four scenarios where a smart device, Figure 3a, was tracked in a virtual environment. These applications, shown in Figure 3, were respectively (b) a virtual lightsaber, (c) a futuristic slingshot with vibrotactile feedback, (d) an in-VR digital camera, and (e) a simulated messaging application. These applications were selected to showcase a varying degree of functional integration of the smart device in a virtual setting. In (b), the tracked smart device served as a passive haptic proxy object by overlaying it with a virtual lightsaber which could be turned on and off using touch interaction. For (c), participants were able to shoot a stack of cans with a futuristic slingshot by sliding their finger downwards over the screen of the smart device. Here, the smart device served as a functional controller augmented with simple vibrotactile feedback from its actuators to increase the plausibility of the device. Furthermore, with (d) participants used the smart device as a virtual camera and were able to take pictures of the environment and selfies. The recorded images remained persistent outside of the virtual environment on the used device. The idea behind this application was to transport existing smart device logic into the virtual setting. Lastly, to investigate the scenario of social interaction while immersed, participants were presented with a simulated messaging application in (e). Here, a fixed number of contacts were presented inside the application, with which the experimenter could simulate incoming messages. Our tracking mode was set to use the optical marker tracking as this method was found to provide the most consistent results.

The final setup consisted of an HTC Vive Pro connected to a laptop running Windows 10, with an Intel Core i5-8300H 2.3GHz, 8GB RAM and an NVidia GeForce 2060 RTX. For the smart device, we used a Google Pixel 3 with a matte screen protector to reduce screen reflections. During tests, performance was stable with an average of 80 frames per second.

4.2 Participants

From our university campus, we recruited a total of 10 participants (2 female, 8 male, 24 – 33 years, $M = 27.3$, $SD = 2.87$) with backgrounds in Software Development, Computer Science, Bioinformatics, and Human-Computer Interaction Research. When asked about their hand dominance, 9 participants indicated to be right-handed while 1 participant stated to be ambidextrous. All participants indicated to have either normal or corrected visual acuity. All participants confirmed that, to the best of their knowledge, they did not have any visual impairment, nor any impairment of their haptic perception, such as arthritis or hypoesthesia (numbness).

Participants rated on a scale from 1 (= never) to 4 (= daily) how often they used Virtual Reality (1, never; 6, once or a few times; 3, regularly). When asked about their daily smart phone usage, 4 participants indicated to spend a maximum of 2 hours on their phone, 5 indicated to use their phone between 3 to 5 hours, while one participant indicated to used their device for 9 hours every day. Here, all participants indicated to use their devices to communicate through calling or sending messages, and for retrieving

(a) HMD Camera view **(b) Lightsaber** **(c) Slingshot** **(d) Camera** **(e) Messenger**

Figure 3: A smartphone is tracked using on-screen markers in (a) and represented in VR as (b) a lightsaber, (c) a catapult with haptic feedback, (d) an in-VR digital camera, and (e) a simulated messaging application.

information from the internet. Nine out of 10 participants indicated their smartphone was used to connect to social media and the same amount of participants used their device as a mobile music player, while 8 participants also considered it a device for productivity, e.g., by using it as a calendar. Only 4 participants typically used their device for mobile gaming and the same amount used it for fitness tracking. Only 1 participant watched videos on their device, while 1 participant actively used it as a camera.

The study lasted between 30 and 45 minutes depending on the speed of the participant. Participation in the study was voluntary and could be stopped at any time. Compensation was given in the form of delicious candy.

4.3 Procedure

The study consisted of two parts, i.e., a guided virtual experience phase and a semi-structured interview phase. In the first part, the experimenter asked each participant to enter the virtual environment by putting on the HMD. Here, the participant was asked to activate and try out the four different scenarios depicted in subsection 4.1. During this exploration, participants were asked to go through a think-aloud protocol to express their initial impression for each application utilizing a smart device in the virtual environment.

During the second part of the study, a semi-structured interview inquired participants about their impressions and opinions related to the use of a smart device in VR. Here, the interview first assessed participants' general smart device and VR experience, followed by their impressions of combining these technologies together. Lastly, for each application scenario presented in the first part of the study, the experimenter elaborated on its intended use and asked participants about their experience of this application scenario, if they saw benefit in such a scenario for a real application, and if they could come up with similar scenarios focused on smart device usage in VR. Here, participants were provided screenshots of each application, and were able to note down or illustrate potential ideas.

After the experiment, participants completed a post-study questionnaire inquiring about their demographics. For analysis of the results, each study was video recorded. All participants provided written consent with regards to data protection regulations. In terms of COVID-19, local regulations were adhered to ensure potential contact tracing and provide health protection.

5 RESULTS

To analyse our results, we followed a thematic analysis [1] approach where two independent researchers processed the transcribed video recordings, resulting in the following themes:

Interaction & Affordances. When asked how they experienced interacting with the virtual environment using a smartphone, all participants provided positive comments. The interaction "felt familiar" (P2, P8, P9) and "intuitive" (P4, P6, P8), potentially resulting in a smoother learning curve (P2). Some actions "seemed to be easier to accomplish using a phone", i.e., zooming (P8), and the use of a phone could provide even more functionality to VR (P4). One participant stated it would be easy to transfer knowledge of interacting with a smartphone to a virtual environment (P6). Moreover, we noticed users even expected some interactions to work similar to known interactions. For example, one user pressed the power button to shut down the lightsaber (P1), another used the volume button expecting the camera to capture a picture (P2), and another performed a pinch gesture to zoom into a picture (P4).

The interchangeable representation of the smartphone made the device become part of the virtual world (P2), and was considered a logical (P1) and useful integration (P3). Here, participants indicated the physical affordances, such as shape or size, needed to be taken into account to serve realism (P1, P3, P4, P9, P10), and the virtual representation needed to serve the task in the virtual environment (P2), and be integrated based on the virtual context (P10).

As a device that we carry with us, the smartphone felt like a "personal controller" (P2) that could easily be used as a secondary device in VR (P8, P10). Moreover, it was considered to provide an awareness of events outside the virtual environment (P9) and potentially decreases the need for context switches to remain connected (P2, P3, P4). Compared to a standard VR controller, the larger touch screen was appreciated (P3) and showed potential for extending interaction through known gestures, such as pinch-to-zoom (P10), point-and-click (P5), or virtual lens interaction (P9). The touch-screen was considered a better interface for typing text (P5, P9), drawing (P1), or locomotion (P5).

Scenario & Application Insights. In terms of applications, general preference went out to the virtual camera scenario. Here, participants indicated to specifically like the notion of taking "selfies" in VR. The fact that pictures were available on the device outside the VE was appreciated by all users. Moreover, participants indicated they would like to share their virtual pictures with others using social media (P1, P2, P6, P9, P10), as selfies were considered to "provide a better context" of the virtual experience (P2). Participants requested the functionality of taking pictures of bystanders (P2, P3, P4), editing pictures (P5, P6), or using the camera to 3D-scan real objects for translating them into the virtual space (P5). Seven participants envisioned the use of a smart phone in VR gaming related scenarios, examples including a drawing interface for Pictionary, a device for social communication, for streaming, or to simulate different tools and weapons.

Users indicated the appropriation of smartphone functionality to the virtual environment to be beneficial. Here, participants requested the addition of certain functions, such as being able to control music (P2, P8), place or take calls (P1), take notes (P8), set timers (P10), observe the current time (P6), or retrieve information online (P1, P2). One user (P4) noted the more detailed vibrotactile feedback of smartphones to be a major improvement. Some users (P2, P6) indicated it would be worthwhile to transport the entire smartphone's functionality to the virtual setting, however this raised concerns of accidentally triggering actions, e.g., accidentally starting a phone call (P2, P9). Suggestions were made to extend the framework's device compatibility by supporting other devices, e.g., Google Nest (P8), or smart watches (P5).

Issues & Concerns. Participants also noted some issues and concerns with the current approach. The visual tracking caused a noticeable delay in tracking when waving the virtual lightsaber (7 users), and tracking was lost when the phone was rotated away from the cameras (5 users). For the latter, one user commented that this disrupted their muscle memory reliability during interaction (P3). Additionally, 2 participants noted minor artefacts with the background substraction algorithm, such as a coat suddenly appearing. Lastly, some expressed concerns about damaging their device during the experience (P3, P9), while another stated the use of a smartphone in VR would build on "phone addiction" (P4).

6 DISCUSSION

From our results, we see that the integration of a smart device in VR using our framework was assessed positively. As a device that we carry with us, a smartphone has the potential to become a personal controller for VR. For example, through dynamically integrating smart devices, the user would not only carry with them a physical controller, but also a set of functionalities, which could build more personalized interactions in shared virtual settings.

As users are familiar with handling their personal device, smartphone interaction in VR was indicated to provide a sense of device familiarity and intuitiveness. On a functional level, this underlines potential for appropriating known smart device interactions for accomplishing tasks which are more complicated in VR, e.g., typing text, or sketching. On a logical level, users are also familiar with the applications they frequently use on their device and have an understanding how such applications can be used in virtual settings. Transporting a smartphone's functionality could therefore extend the capabilities a VE offers through different levels of integration, similar to how related work investigated purpose-centric appropriation of everyday objects [32]. For example, by using see-through solutions, mobile applications can be utilized without the need for augmentation and by building upon the social features of a smart device, bystanders can be included in to the virtual experience [12, 34]. Furthermore, through contextualized integration, the content of a smart device can be represented in a manner that would support the plausibility of the virtual illusion, cf. [35].

In our work, we see that smart devices can function as haptic proxy objects for immersive virtual environments. As users perceived such scenarios positively, we posit that smart devices have the potential to support and extend existing work on haptic feedback in VR. For example, by overlaying pseudo-haptic interfaces onto a smart device's virtual representation, its virtual interaction can be improved [29]. Moreover, we see potential for using smart devices in the field of haptic design for VR [6, 27]. Similar to previous work [5], smart device sensors could capture physical properties in the real world, to transport their properties to the virtual setting, or serve as an intermediate for fabrication of tactile artifacts [7]. Recent work has underlined that vibrotactile feedback can be designed using vocal expressions [4], or through haptic instruments using touchscreen interaction [28]. Here, smart devices lend themselves as integrated and fully-functional interfaces to record users' intentions during in-situ design. Additionally, the connectedness offered by smart devices has the potential to support sustainable haptic design through online sharing and reuse [26].

However, smart device integration does create some concerns. Any given implementation needs to ensure primary device functions, such as starting a call, are not accidentally triggered, and safety precautions for not damaging the device need to be considered. While smart device integration in a VE shows great potential, future work needs to consider social or behavioural aspects, such as its effect on phone addiction.

7 CONCLUSION

In this work, we presented *VRySmart*, a framework built in Unity to integrate smart devices, such as smartphones or tablets, into virtual environments. Using our framework, we created four scenarios, i.e., a virtual lightsaber, a futuristic slingshot with vibrotactile feedback, an in-VR digital camera, and a simulated messaging application. Using these scenarios, we conducted a user study consisting of a think-aloud exploration phase and a semi-structured interview phase. Our initial results show users' positive attitudes towards using a smartphone as a multi-functional controller for VR applications. While device familiarity and intuitiveness underline the potential of different levels of integrating smart devices in virtual environments, on a conceptual level, concerns such as privacy and accidentally triggering or damaging the device need to be addressed. Building upon these results, we aim to explore deeper integration of smart devices in VR by extending our framework's device compatibility and building upon related work for seamlessly integrating notifications while maintaining the plausibility of the illusion.

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