

Influence of Passive Haptic and Auditory Feedback on Presence and Mindfulness in Virtual Reality Environments

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Figure 1: Participant sits on 2x2m² artificial grass floor while conducting a mindfulness task in a virtual nature environment.

ABSTRACT

Virtual Reality (VR) is increasingly being used to promote mindfulness practice. However, the impact of virtual and multimodal interactive spaces on mindfulness practice and presence is still underexplored. To address this gap, we conducted a mixed-method user study ($N=12$). We explored the impact of various multimodal feedback, in particular tactile feedback (passive haptic feedback by artificial grass) and auditory feedback (footstep sound) at feet level on both mindfulness and presence. We conducted semi-structured interviews and collected quantitative data through three validated questionnaires (SMS, IPQ, WSPQ). We found a significant effect of passive haptic feedback on presence and mindfulness. Tactile

feedback improves the focus on the self, facilitates spatial presence and increases involvement. Auditory feedback did not significantly affect presence or mindfulness. While ambient sound was perceived as beneficial for presence, footstep sound subjectively disrupted both presence and mindfulness. Based on our results, we derive design recommendations for multimodal VR applications supporting mindfulness practice.

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; *HCI theory, concepts and models*; Visualization systems and tools.

KEYWORDS

Virtual Reality; Presence; Mindfulness; Haptics; Auditory Feedback; Ground; Surface

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1 INTRODUCTION

Mindfulness practice positively impacts mental well-being and health [51]. It is increasingly becoming a part of our everyday well-being routines. For instance, meditation as one aspect of mindfulness practice was considered the fastest growing trend in the US in 2018 [15]. There is not one set definition for mindfulness and mindfulness practice, partly due to its long history and different mindfulness traditions [14, 18, 40]. However, in contemporary psychology, mindfulness is often defined as a mental faculty of intentionally being aware of the mind, body, and physical environment in present-time [74], while being in a mental state of acceptance [31, 32]. Mindfulness can be trained through varying practices, among others guided mindfulness meditation [31], walking meditation [16] or short-term mindfulness training programs [39]. To illustrate, people practising mindfulness might train to stay focused on a specific object or activity (e.g. respiration, sensory information) [74] while cultivating a non-judgemental attitude [39].

On the other hand, technology is increasingly used to support mindfulness practice [3]. In 2020, 370 mindfulness-related smartphone apps such as *Calm* or *Headspace* could be downloaded [40], trend increasing. In 2021 mindfulness tutorials such as *Headspace Guide to Meditation* were released on the streaming service Netflix. Furthermore, also Virtual Reality (VR) is increasingly used to practice mindfulness [24, 47, 79]. To support, multimodal VR environments and spaces offer great benefits for mindfulness, increasing positive emotions when conducting mindfulness exercises [66] and fostering relaxation while reducing mind wandering [3].

Nonetheless, with new technologies the ICMI, VR and HCI communities are also facing new challenges. We hypothesise that when multimodal cues differ between VR and reality, especially when visual and auditory cues in VR mismatch from haptic sensations and auditory cues in reality, it might break presence and disturb mindfulness practice. To elaborate, presence describes the subjective feeling of being there in the VE [82], and often successful VR interventions, e.g. VR rehabilitation [13] or empathy enhancement [62], can be traced back to an achievement of high presence. Among others, presence is increased through high realism in the VE [28], which can be achieved through multimodal stimuli [25], e.g. by applying physical laws, environmental sounds, haptic feedback [37] and the correct rendering of walking over virtual grounds [42]. As, by definition, mindful practice increases the awareness of oneself and the surrounding of the present moment [32], low presence through mismatches of visual, tactile and auditory cues could distract while high presence could support attention to body and mind. As an example, use cases of VR are mostly limited to enclosed spaces such as the living room or scientific laboratories, both of which consist of static flooring such as carpet, wood, or linoleum. However, most mindfulness apps use nature settings to immerse their users [79], as experiencing nature significantly increases relaxation compared to urban settings [16]. As stepping on hard surfaces in reality feels different and creates other distinct stepping sounds than moving on virtual grass, it creates a mismatch between visual, auditory and haptic cues which can distract users from mindfulness practice.

Although other work has shown that footstep sound [20] and tactile feedback [34, 42] can increase presence, that presence can facilitate mindfulness practice [47, 66], and that immersive and multisensory VR can support presence and mindfulness [3, 47, 66], empirical knowledge of how a mismatch between visual, auditory and haptic cues affects presence and mindfulness is lacking so far [43].

To address this research gap, we explore to what extent multimodal stimuli at feet level affect presence and mindfulness. Multimodal stimuli comprises tactile feedback by passive haptics in the form of (mis-)matching ground (linoleum and artificial grass) and auditory feedback by playing footstep sounds adapted to the material of the ground while walking in VR. This paper contributes the following: (1) a mixed-method within-subject study ($N=12$), (2) insights regarding the effect of passive haptics and auditory feedback on presence and mindfulness, and (3) a set of implications to inform the design of future VR applications that strive to provide meaningful mindfulness interventions.

2 RELATED WORK

Technologies within interactive spaces to support mindfulness practices and well-being are becoming increasingly important in people's well-being routines [3, 70]. Concurrently, popularity of mindfulness practices has grown over the past few years [46, 58, 70]. In the next sections, we will define mindfulness and its benefits for well-being and health. Then, we will discuss the relationship of mindfulness to presence in VR settings, and to multimodal feedback, focusing on tactile and auditory feedback.

2.1 Benefits of Mindfulness Practice

Partly due to its long history, a variety of different mindfulness definitions exist [14, 18, 40]. This paper follows a definition rooted in contemporary psychology, in which mindfulness is defined as a mental state of present-moment awareness, thus intentionally focusing on present-time aspects [31]. Following this definition, mindfulness encompasses two components: present-moment awareness, i.e. paying attention to specific physical or bodily objects and/or mental states in the present moment (i.e. *what* experience a person focuses on), and mental attitudes, e.g. curiosity, perceptual sensitivity to stimuli, acceptance of present moment experiences (i.e. *how* a person engages with experiences) [5, 39, 60].

Benefits of mindfulness practice are manifold. For instance, mindfulness increases well-being [9, 68]. Also, mindfulness positively affects mental health as an integral part of holistic health and effective functioning in society [51]. Furthermore, on a cognitive level, mindfulness improves executive attention [1] and enhances creativity [17, 29], which in turn can support flow and presence [83]. Amongst other aspects, mindfulness further positively influences visuo-spatial processing, working memory, and executive functioning [84]. Our study focuses on the question on how to best utilise immersive multimodal features of virtual worlds to enable the most effective mindfulness practice.

2.2 Relation of Mindfulness, Immersion and Presence in VR

VR is increasingly used to support mindfulness practice [3]. VR was found to increase relaxation [3, 53], support mindful meditation [21, 47], and reduce mind wandering while preserving attention resources [3]. Seabrook et al. [66] found that mindfulness exercises in VR increase state mindfulness and positive emotions. One reason why VR can successfully be used to foster mindfulness is because it can immerse users by stimulating their perception of sensory, vestibular, proprioceptive, and interoceptive channels [6, 56]. The better VR succeeds, e.g. by addressing multisensory experiences, the greater the user's presence [56].

Both high immersion and high presence benefit mindfulness practice in VR [66]. Presence is the subjective psychological state of being in one place (the VE) while actually physically situated in another (the reality) [82]. High immersion reduces distractions from reality, which favours presence and provides the opportunity to dive into different virtual locations, which benefits mindfulness practice [47]. Further, VR was found to increase relaxation [3, 53], support mindful meditation [21, 47], and reduce mind wandering while preserving attention resources [3]. Seabrook et al. [66] found that mindfulness exercises in VR increase the state of mindfulness and positive emotions.

Also commercial apps using the benefits of VR can offer support for mindfulness practice. As discussed in Wagener et al. [79], most commercial VR apps for mental health do not clearly differentiate between terms such as mental health, well-being, relaxation, meditation and mindfulness, making it almost impossible to clearly differentiate between the terms. Commercially available VR apps offer realistic and calming natural settings, such as beaches ¹, lightly wooded meadows ², and mountainous VEs ³. Others place the intervention in more abstract space-like environments ⁴. Some also include mindful and meditative games that motivate deep breathing ⁵, repetitive motion ⁶, and slow body movement ⁷.

Inspired by these approaches, we endeavour to build an understanding of the interplay of mindfulness and presence within a carefully designed environment. Our aim is to derive insights on how to build multimodal mindfulness spaces in VR to increase the well-being of users.

2.3 Relation of Mindfulness with Multimodal Feedback in VR

VR offers potential advantages to support mindfulness practice in multi-sensory VEs [3]. In the following, we will outline examples of related work which illustrate how tactile and auditory feedback can be created in a multimodal VE and how it can potentially foster mindfulness.

Haptic feedback is created by somatosensory pressure receptors informing users about physical contact with objects [80]. For example, haptic feedback can be created through imitating forces,

movement and other sensations felt when touching objects [42]. Such tactile sensations can be provided by active (generated by vibrotactile actuators or motors [48]) or passive haptics [38, 48]. Passive haptic feedback either uses corresponding analogue materials with the same physical properties, e.g. shape and texture [48], or proxy materials mimicking those properties [19]. It has been shown that tactile feedback may increase presence [42] and emotional responses [30, 45]. Furthermore, it can lead to more realistic experiences [76], and in turn it can be perceived as stronger in high-realistic environments [59]. Though active haptic feedback has been shown to increase presence more than passive haptic feedback [34], devices for active haptic feedback are often bulky, heavy and restrictive [34]. To the best of our knowledge, the relevance of tactile feedback for mindfulness practice has not been researched yet. Consequently, our study inquires the impact of passive haptic feedback on mindfulness experiences in VR.

Auditory cues provide important information about the entire environment [33]. For example, ambient sound creates the sense of being surrounded by a spatial scene [35] and facilitates the localisation of objects [35]. Auditory cues such as footstep sound require a controlled setup to superimpose sound with real-time body movement. Possibilities to achieve this include HMD's sensor data [33], VR trackers [26], and microphones [49, 67, 77]. However, all those approaches face challenges, e.g. through occlusion or unintentional noise artefacts. To avoid those, some studies rely on force-sensitive resistors (FSRs) instead. FSRs capture the pressure when the foot touches the ground and a microcontroller communicates this input to the VE. They can be positioned underneath the shoe sole [26], at insoles [44, 71], and at multiple foot areas [44], although the highest pressure is exerted at the heel [71]. Research showed that auditory cues detected by FSRs can increase the users' presence in VR and the awareness of the own body posture [26], and can facilitate mindfulness practice by creating interactive soundscapes, e.g. in meditative walking experiences [16, 63] or in respiration awareness training [54]. Contrarily, improper sounds can easily lead to breaks in presence [26]. Instead of using auditory feedback to inform mindfulness practice, in our paper, we investigate the effects of auditory feedback on mindfulness. To our knowledge, the effect of auditory feedback on mindfulness has not been researched so far.

3 VIRTUAL ENVIRONMENT DESIGN

Commercial VR apps that support mindfulness (see section 2.2) are designed in heterogeneous ways. Literature has shown that mindfulness and presence are both influenced by the level of fidelity and the degree of realism of virtual environments [28]. Also, related work has shown how easy both mindfulness and presence can be disturbed [26, 37]. Thus, we took special care with creating our study setting. Consequently, we conducted an exploratory pre-study.

3.1 Pre-study

In a between-subjects pre-study with $N=20$ (9 female, 11 male) with an average-age of 22.9 years ($min = 17$ years, $max = 30$ years), we tested our design in regard to presence. Participants either experienced the VE with or without artificial grass as flooring. The

¹e.g. Guided Meditation VR, Ozential, Perfect Beach VR, Zen Zone

²e.g. Guided Meditation VR, Mind Labyrinth VR, Nature Treks VR

³e.g. Mind Labyrinth VR, Wise Mind VR

⁴e.g. Conscious Existence, Guiding Star VR Meditation, Zen Zone

⁵e.g. Prana, Zen Zone

⁶e.g. Re Mind VR, Wise Mind, Zen Zone

⁷e.g. Guiding Star VR Meditation, Wise Mind

participants did not see the artificial grass when entering the lab. After participants finished with the task of picking up apples (for more information see subsection 4.3), they filled out the IPQ [64] to indicate their level of presence. Additionally, their behaviour during the study was analysed to gain further insights [73]. In addition, semi-structured interviews were conducted. Both, the interviews and comments voiced by participants during the study were audio recorded and transcribed. The qualitative data was analysed using thematic analysis [7].

We found no significant effects for the two conditions, calculated with the Wilcoxon rank sum with continuity correction on a .05 confidence level. Presence was above average, scoring above 3 for all IPQ subscales. Our qualitative findings showed that all participants experiencing the grass haptic feedback expressed positive feedback. All participants ($N=20$) were positively surprised by the flooring, and reported a perceived increase in presence. Some ($N=13$) also suggested further adjustments of the VE, such as sound and ambient sound.

3.2 Final Virtual Environment

Based on the pre-study results, we adjusted the virtual environment and study design. We designed a high fidelity VR scene as realism has a positive influence on presence [28]. In a natural setting, which ameliorates mindfulness and relaxation [16], participants entered the VE in a wooden hut which was equipped with rustic furniture and interactive objects such as plates on a table. When exiting the hut, participants experienced a grassy front yard with an apple tree, which is surrounded by a fence (see Figure 1). The fence restricted the playable area for the users and visually separated the yard from a meadow on which several animated animals roamed, e.g. rabbits and deer. This whole scene was placed in a mountainous location. Also, the sun was shining bright and, based on inquiries of some pre-study participants, the scene included ambient sound of birds chirping and wind rustling through trees and grass.

3.3 Implementation

Passive haptic feedback is provided by a 2×2 m² artificial grass flooring. Further, a 2×2 m² linoleum flooring simulated the wooden floor of the hut and was used to guarantee a maximum difference of flooring. Artificial grass was placed at the virtual door sill so that the ground noticeably changes when stepping out of the hut. As described in subsection 2.3, a reliable solution to detect footstep sound is a force sensitive resistor (FSR) attached to a foot. We used an ESP8266 microcontroller unit (MCU) with the NodeMCU firmware, which is powered by a lithium-ion battery (3.7V) and a connected FSR. The electronic parts are protected by a plastic box case and strapped to the ankles (see Figure 2). The pressure sensors are sellotaped to the heel and additionally fixed with a disposable sock. When the heel hits the floor, the sensors are activated and send a foot identifier to differentiate between left and right foot, and a pressure value to a TCP server in Unity. Footstep sound is only played when the pressure value surfaces a certain threshold to mitigate false signals. As suggested by Hoppe et al. [26], the virtual location of the sound source is placed at the user's feet to create a more realistic atmosphere. Further, grass stepping sounds, taken



Figure 2: Attachment of the sensor at the heel and MCU at the ankle.

from Fesliyan Studios⁸, randomly varied between seven samples to generate a more realistic and diversified soundscape. As a further change based on results of the pre-study, taking off the HMD to fill out questionnaires accounts as a break in presence [2, 66]. Thus, to ease participation [55] and to mitigate those breaks that can be disengaging for mindfulness practice [66], we embedded the questionnaires into VR based on the concept by Alexandrovsky et al.⁹ [2].

4 USER STUDY

The effect of passive haptics in combination with footstep sound was evaluated in a user study. The study was designed as a within-subject experiment with two independent variables with two factor levels each: tactile feedback (grass G and no grass NG) and auditory feedback (with footstep sound F and without footstep sound NF). The order of conditions was counterbalanced and randomised (Latin square) to minimise sequencing effects.

4.1 Participants

We used our extended social network and snowball sampling to recruit participants. Twelve participants (2 female, 10 male) that have not been part of the pre-study with an average age of 25.5 years ($min = 18$, $max = 30$ years) participated in the study on a voluntary basis without receiving remuneration. Two participants had never tried out VR in their lives, nine had used it once or occasionally, one several times a week. Three had specified to work with VR.

4.2 Data Collection

We gathered quantitative and qualitative data from the participants to understand the potential effect of passive haptic and audio feedback on mindfulness and presence. Quantitative data was collected

⁸<https://www.fesliyanstudios.com/royalty-free-sound-effects-download/footsteps-on-grass-284>

⁹<https://github.com/alexandrovsky/VRquestionnaires>

from three validated questionnaires (SMS, IPQ and WSPQ). Further, we gained qualitative insights through interviews.

4.2.1 Measures. The following dependent variables were measured for both conditions: **Mindfulness** was measured by the state mindfulness scale (SMS) [75]. In contrast to other self-report measures (i.e. state-Mindful Attention Awareness Scale [10] and Toronto Mindfulness Scale [36]), SMS reflects mindfulness as the objects of mindful awareness (i.e. what experience a person focuses on, including physical sensations and mental events) and the qualities of mindful awareness (i.e. how a person attends to experience, including perceptual sensitivity to stimuli, deliberate attention, willingness to feel, curiosity) [60, 75]. The 21-items, rated on a 5-point Likert scale, are split into two subscales that measure bodily sensations in the SMS-body subscale (maximal possible scoring = 24) and attention to and awareness of mental events (e.g. emotions, patterns of thought) in the SMS-mind subscale (maximal possible scoring = 60). Higher scores reflect higher levels of state mindfulness. A summation of the subscales results in the total score of mindfulness.

Presence was measured with two scales. First, we used the Igroup presence questionnaire (IPQ) [64]. The IPQ is split into four subscales, general presence (sense of being there), involvement (attention devoted to the VE), experienced realism (subjective experience of realism in the VE), and spatial presence (feeling physically present in the VE). Further, we used the Witmer and Singer Presence Questionnaire (WSPQ) [81] for presence measurements. Although criticised, among others due to its length [72] and not differentiating enough in their question setting [65], it is the most often used presence measurement in literature [2, 55]. It is divided into four sub-scales: involvement (inclusion of the user), interface quality (resolution of the VE), sensory fidelity (visual, haptic and auditory elements), and adaption/immersion (interaction possibilities and adaptability of the VE).

4.2.2 Interview Protocol. We conducted semi-structured interviews that lasted on average 22.22 min, asking about general user experience, their most memorable experiences in the study and what they focused on. All audio recordings were transcribed verbatim and imported into Dovetail¹⁰. Two authors both coded two interviews using open coding. Then, a coding tree was established through iterative discussion. The remaining transcripts were coded individually by one author using the coding tree. A final discussion session between two authors was conducted to identify emerging themes using thematic analysis [8]. The interview protocol can be found in the supplementary material.

4.3 Procedure & Tasks

After welcoming and briefing, participants themselves (due to hygienic restrictions) fixed the sensors under their heel with sellotape and a pair of try-on socks, attached the prototype to their ankles (see Figure 2), and made sure that sitting was comfortable. They put on the HMD (HTC Vive Pro) with a wireless adapter to offer a cable-free solution. Throughout the study they used one controller in their dominant hand.

As an introduction to the study, participants envisioned being on vacation in a cabin in the mountains, and that they wished to feed some animals by collecting the respective amount of apples. The apples laid on the grass in the front yard and participants were asked to put them in a basket, which was located inside the hut. This counting task ensures that participants encounter different ground surfaces with their hands and feet when switching between different flooring material. Afterwards, participants took a seat on the ground in the front yard to perform a 3-minutes guided relaxation exercise based on the mindfulness app *Headspace*¹¹ that was played via the HMD headphones. Participants were free to choose if they wanted to close their eyes and keep the controller in their hand. Detailed information can be found in the supplementary material. Thereafter, participants filled out the in-VR questionnaires (SMS, IPQ, WSPQ) inside the hut. This guaranteed space for the experimenter to change the ground surface for each condition (i.e. preparing or removing grass) and to reduce breaks in presence for the participants. This procedure was repeated in total four times. Post-study, participants were asked for their preferred condition and post-test interviews were conducted remotely.

5 RESULTS

Based on the user study, we gathered qualitative insights from the interviews and quantitative results from the questionnaires. Our findings will be presented in this section.

5.1 Qualitative Results

Based on our qualitative inquiry, four themes were derived from the data: *Iterative Immersion*, *Multi-Sensory Experience*, *Simplicity* and *(Virtual) Reality*. Our findings are described below and illustrated with excerpts from the interviews.

5.1.1 Iterative Immersion. The first theme derived from our data focuses on how relaxation and presence were enhanced through an iterative process. The theme consists of two codes: *Iterative Entry* and *Iterative Procedure*.

Participants enjoyed being gradually immersed in the VE. As a first step, they put on the HMD and were located inside the virtual wooden hut. In a second step the participants themselves opened the door and entered the natural scene. This two-step process made them more relaxed and they felt that they were able to behave more freely. Participants described similar experiences when stopping the virtual experience and re-entering reality after the study was done. As a last step, they filled out the in-VR questionnaires inside the hut, which, first, again changes the environment back to a closed space more similar to the room in reality. Second, the task of filling out questionnaires was encountered as a tedious task, detached from the actual VR experience, therefore providing a transition between the virtual experience and the lab environment. While some participants reported benefits of the iterative procedure and sequence within the study, some participants assessed the duration of the study as tedious, too long or boring. The following statement illustrates how the iterative process allowed participants to feel safe in the VE and being able to foresee that nothing dramatically changes:

¹⁰<https://dovetailapp.com/>

¹¹<https://www.headspace.com/>

It took me a few iterations to really get into this world. But from round to round, this meditation or relaxation exercise contributed more and more to the fact that the immersion got better. (P3)

5.1.2 Multi-Sensory Experience. The second theme encompasses the influences of different modalities on presence and mindfulness. We split this theme into four codes according to computer-human modalities in HCI [4]: *Vision*, *Tactition*, *Audition*, and *Uncommon Modalities*.

Participants emphasised that *vision* - more precisely being in an aesthetically pleasing environment, thus allowing for immersion - is the most important modality. Further, they also described that the beauty of the environment, especially the brightness, colours, light reflexes and being in nature, supported them in their relaxation.

The second code, *tactition* encompasses findings about the relationship of haptic sensation with presence and mindfulness. All participants enjoyed the feeling of grass. The material properties (warm, soft) was praised especially in contrast to the linoleum flooring (cold, hard), and made the setting more comfortable and, effectively, more relaxing. We also found that haptic feedback enriches mindfulness. Participants reported that by stroking the grass, they concentrated more on their own body and felt their focus shift to the self. P5 clarifies:

And I think that's why I found it so pleasant to really caress this grass with my hands, because it helped me to focus a bit on myself and my body. (P5)

The third code, *audition*, evolves around effects of various audio outputs. First, participants positively commented on the ambient sound. All participants explained that the sound atmosphere was convincing (except when the loop ended), increased realism and presence, and that it facilitated relaxation during the mindfulness task. Some participants mentioned that they closed their eyes to concentrate on the soundscape, and that they could not differentiate between reality and VR anymore.

Not as conclusive were the results for the stepping sound. Although some reported an increase in presence, because it complemented the overall experience, or that it did not matter because walking on grass would only make a soft sound in reality as well, most participants concentrated too much on technical issues to accept this modality. They criticised that the volume was too loud, the tone too unconvincing, the appearance too temporally displaced, which all in all led to breaks in presence. Some participants also mentioned, that the sound made them aware of their walking habits, which further decreased their presence.

Moreover, participants reflected on the benefits of adding *uncommon modalities*. Some participants noted that the more senses were involved the better because it reflects reality. They desired olfactory elements such as smelling mown grass, addressed thermoception by feeling the sun's warmth, and thought about adding ventilators to simulate a breeze. Those would further enhance the realism of the VE, increase presence, and, hence, participants assume it would improve positive affect and mindfulness. However, some participants also decided to filter out overlapping unconvincing modalities that lacked in authenticity so that their presence and mindfulness is not disturbed.

5.1.3 Simplicity. The third theme, *simplicity*, focuses on the design of the virtual experience. First, participants aimed to discover limits of VR, either by inventing games such as stacking apples to test physical laws or by checking how well vision and tactition are aligned, as well as how well objects in VR resembled their real counterparts. Second, participants were curious and attempted to reduce insecurities. Thereby, the simplicity and iterations of the study itself helped because it increased the familiarity of the VE. These experiences resulted in higher presence and increased relaxation, because participants were sure that nothing new or scary, like a jump scare, would happen to them. One explained:

It was a nice, simple process. And the clearer it became, the more relaxing it was. (P3)

Some participants decided to savour the moment by closing their eyes. In contrast, others felt that the virtual experience is 'too precious to close the eyes' or that they had to keep their eyes open for the sake of the study.

As a last aspect regarding the theme simplicity, the instructions providing guidance during the mindfulness task were not memorable. Although participants could remember the calming sound of the voice, they were often undecided of its gender and reported, that after the first introduction of the task, they stopped listening to the voice in the following iterations to instead fully concentrate on relaxing.

5.1.4 From Reality to VR to Reality. The last theme describes the loop of how participants were reminded of reality while being in VR, and in turn how their virtual experience influenced their lives outside of the virtual experience. Some participants mentioned that it felt somewhat like a break or a short vacation from their everyday lives, contrasting the busy daily schedule they normally experience. On the other hand, some were reminded of real experiences they made as they connected their memories with the virtual experience based on the similarities of what they felt:

During the study I sometimes felt as if I were in this park [in the neighbourhood]. Maybe a little bit away from it [other people], it was quiet, it was nice, I could hear birds, nature around me, so to speak. Then I just thought back a bit to that feeling. (P4)

We also found that some imagined using the VR app again in the future to feel the same form of relaxation. Further, some reported a lasting effect of relaxation even after the study had ended. Some participants were even inspired by their experience during the study to change their lifestyles in reality accordingly. They had identified their need for and benefits of mindfulness due to the study:

I actually did that afterwards, I (...) went to the park and sat there, but not on the ground, on the bench and really, I think I just sat there for almost an hour or so. That really helped, I will definitely take that with me for the future, that [mindfulness practice] is beneficial. (P11)

5.2 Quantitative Results

A two-way repeated measures ANOVA was conducted to examine the effect of TACTILE FEEDBACK and AUDITORY FEEDBACK on mindfulness and presence. Results are structured according to the

Table 1: Mean value and standard deviation for the SMS subscales *Body*, *Mind* and *Total*, the IPQ subscales *General*, *Involvement*, *Experienced Realism*, and *Spatial Presence*, and the WSPQ subscales *Involvement*, *Interface Quality*, *Sensory Fidelity* and *Adaptation/Immersion*, calculated for each condition.

Variables	SMS						IPQ								WSPQ							
	Body		Mind		Total		Gen.		Inv.		Real.		Spat.		Inv.		Int.Q.		Sens.Fid.		Adapt.	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
G:FS	17.09	3.53	40.27	8.05	57.36	10.30	4.91	0.7	4.20	1.17	3.73	0.69	5.04	0.80	58.82	8.47	5.36	4.11	27.55	3.93	41.45	5.07
G:Nf	17.36	3.14	43.55	6.56	60.91	9.10	4.73	0.90	4.27	1.29	3.55	1.23	4.48	0.57	55.64	9.99	5.27	4.36	27.09	3.91	40.00	4.17
NG:FS	14.91	3.45	41.36	6.31	56.27	9.00	4.09	0.94	3.57	1.26	3.36	0.88	4.64	0.57	53.36	9.95	5.64	3.75	25.55	5.66	38.73	5.61
NG:NfS	14.91	3.70	38.36	6.68	53.27	9.97	4.18	0.87	3.52	1.37	3.25	0.54	4.64	0.62	54.45	11.12	5.73	4.56	22.73	5.93	37.55	4.27
G	17.23	3.26	41.91	7.36	59.14	9.66	4.82	0.80	4.24	1.20	3.64	0.98	4.94	0.69	57.23	9.19	5.32	4.13	27.32	3.83	40.73	4.59
NG	14.91	3.49	39.86	6.53	54.77	9.40	4.14	0.89	3.55	1.28	3.31	0.71	4.64	0.58	53.91	10.31	5.68	4.08	24.14	5.84	38.14	4.90
FS	16.00	3.59	40.82	7.08	56.82	9.45	4.50	0.91	3.89	1.23	3.55	0.79	4.84	0.71	56.09	9.44	5.50	3.84	26.55	4.87	40.09	5.40
NfS	16.14	3.58	40.95	6.99	57.09	10.10	4.45	0.91	3.90	1.35	3.40	0.94	4.74	0.59	55.05	10.33	5.50	4.36	24.91	5.39	38.77	4.31

questionnaire answers SMS, IPQ and WSPQ of $N=11$ participants (one was excluded due to technical difficulties). Visual inspection of our data in combination with using the Shapiro–Wilk test showed that our data is not normally distributed. Accordingly, we applied the Aligned Rank Transformation (ART). Descriptive statistics of all results are presented in Table 1. We refer to the different conditions combining TACTILE FEEDBACK and AUDITORY FEEDBACK as $G : F$ (grass + footsteps), $G : NF$ (grass + no footsteps), $NG : F$ (no grass + footsteps), $NG : NF$ (no grass + no footsteps).

Participants were also asked to state their most liked condition after the study. Five participants preferred condition $G : NF$, four $G : F$, and two enjoyed both conditions with grass, no matter if step sound was included or not. One could not decide.

5.2.1 Mindfulness. A two-way repeated measures ANOVA was conducted to examine the effect of TACTILE FEEDBACK and AUDITORY FEEDBACK on mindfulness. The test showed a significant effect of TACTILE FEEDBACK on the SMS subscale *Body* $F(1,30)=13.043$, $p=.001$. Further, we found a significant two-way interaction effect of $G : FS$ regarding the subscale *Mind* $F(1,30)=8.14$, $p=.008$. Post-hoc pairwise comparison using Tukey-adjusted p -values showed a significant difference between $G : NFS$ and $NG : NFS$ ($p=.014$). Additionally, we found a significant effect of TACTILE FEEDBACK on the SMS subscale *Total* $F(1,30)=7.986$, $p=.008$. The corresponding boxplot is presented in Figure 3.

5.2.2 Presence: IPQ and WSPQ. Additionally, the two-way repeated measures ANOVA was conducted to examine the effect of TACTILE FEEDBACK and AUDITORY FEEDBACK on presence. The ANOVA showed a significant effect of TACTILE FEEDBACK on all IPQ subscales, namely *General* $F(1,30)=13.19$, $p=.001$, *Involvement* $F(1,30)=7.56$, $p=.01$, *Experienced Realism* $F(1,30)=4.372$, $p=.045$, and *Spatial Presence* $F(1,30)=9.995$, $p=.004$. The results are visualised in Figure 4.

Regarding the WSPQ questionnaire, the test showed a significant effect of TACTILE FEEDBACK on the subscale *Sensory Fidelity* $F(1,30)=17.264$, $p=.0002$ and of AUDITORY FEEDBACK on *Sensory Fidelity* as well $F(1,30)=7.054$, $p<.013$. We further found a significant effect of TACTILE FEEDBACK on *Adaption/Immersion* $F(1,30)=7.981$, $p<.008$. Our findings are visualised in Figure 5.

6 DESIGN RECOMMENDATIONS FOR VR MINDFULNESS PRACTICE

In this work we endeavoured to understand how multimodal stimuli at feet level influence presence and mindfulness. In this section we reflect on our findings and, based on those, outline specific design recommendations for VR applications that strive to support mindfulness practice. We back our qualitative results with findings from our quantitative data. Then, we discuss limitations of our approach and opportunities for future work.

6.1 Iteration for Need Fulfilment

One key finding of our study was the importance of a stepwise entry and exit to facilitate the process of immersion. We provided this by offering an intermediate step between reality (lab environment) and the virtual nature experience in form of a closed virtual space, a wooden hut. We then empowered the user to decide for themselves when they feel ready to enter the described natural scene in which mindfulness is practiced. We hypothesise that this allows for autonomy, one of the universal psychological needs motivating people [61]. Participants also expressed needing time to adjust to reality again after being immersed in VR, because reorientation after high presence takes time [65]. In line with our findings, scholars and VR programmers could help with this transition phase.

Further, we found that an iterative procedure helps the process of immersion. Repetition was perceived as relaxing, and a certain duration is needed to experience presence. Although we cannot derive the minimum duration from our data, it should be clearly communicated to users when they have seen all facets of the experience and nothing else will happen to reduce uncertainty.

Recommendation 1: Virtual environments for mindfulness practice should provide a gradual entry and exit process. Iterative experiences and repetition can be helpful in fulfilling psychological needs (autonomy, competence, relatedness) and reducing anxiety.

6.2 Aesthetically Pleasing But Simple VEs

In our study, we explored the influence of different modalities. We addressed vision (high realism and fidelity), tactition (passive haptics) and audition (ambient and footstep sound). On a general note, we found that participants reacted to visual, tactile and auditive mismatches quite heterogeneously. Some participants felt that the

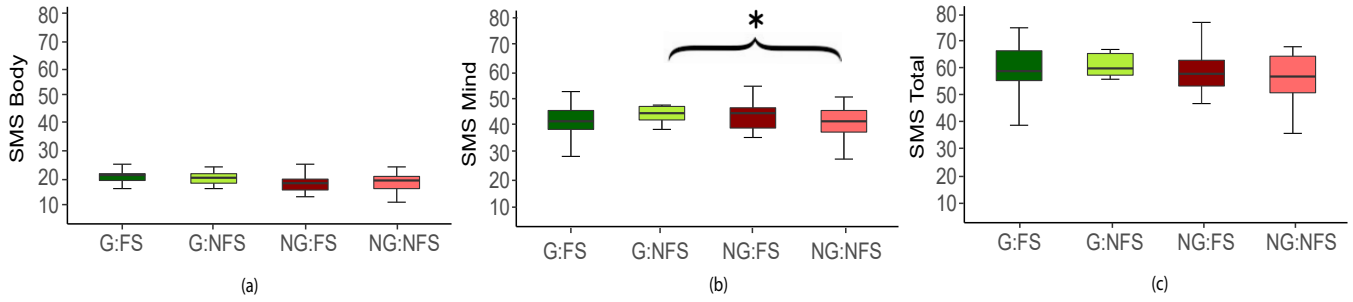


Figure 3: Mean value of SMS subscales (a) Body, (b) Mind and (c) Total for the four conditions. Conditions where TACTILE FEEDBACK is involved are represented in green, conditions where AUDITORY FEEDBACK is involved are shown in red. Post-hoc significance is indicated (* $p < .05$).

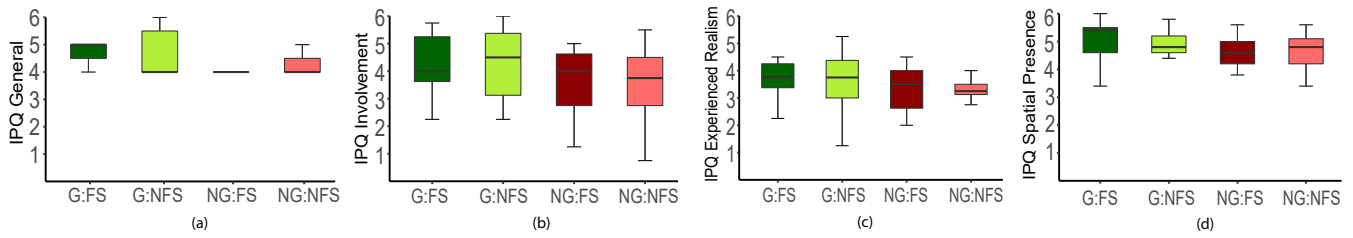


Figure 4: Mean value of IPQ subscales (a) General, (b) Involvement, (c) Experienced Realism and (d) Spatial Presence for the four conditions. Conditions where TACTILE FEEDBACK is involved are represented in green, conditions where AUDITORY FEEDBACK is involved are shown in red.

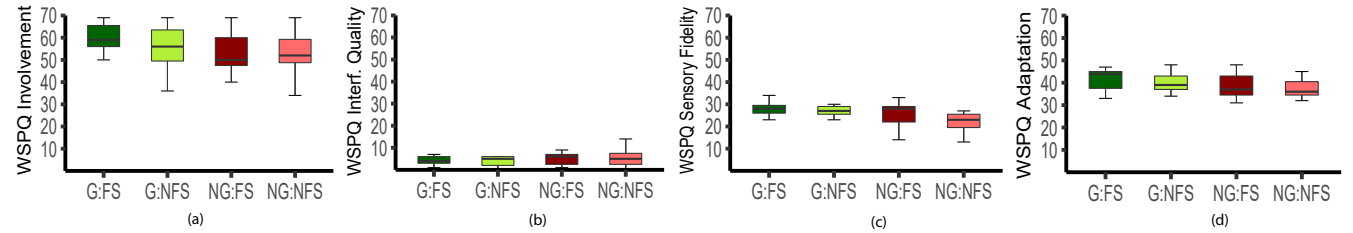


Figure 5: Mean value of WSPQ subscales (a) Involvement, (b) Interface Quality, (c) Sensory Fidelity and (d) Adaption/Immersion for the four conditions. Conditions where TACTILE FEEDBACK is involved are represented in green, conditions where AUDITORY FEEDBACK is involved are shown in red.

more senses were addressed, the better the overall experience. Other participants filtered out aspects that disturbed them, while some experienced mismatches as complete breaks in presence.

Significant results of all the IPQ subscales in respect to TACTILE FEEDBACK and of the WSPQ sub-scales *Sensory Fidelity* ($p < .0002$) and *Adaption/Immersion* ($p = .008$) show the importance for high-quality VEs for presence. We want to especially highlight the results of the sub-scale *Experienced Realism* ($p = .045$), which shows that including tactile feedback increases the perceived realism of the VE. Thus, our results reconfirm the findings of related work (e.g. [76]).

On top of that, our qualitative data showed that for some participants relaxation was enhanced by an aesthetically pleasing virtual experience. Based on that, and as we additionally know that high-realistic visual stimuli in a VE can influence how vibrotactile stimulus is perceived [59], we assume that a pleasing surrounding

might also enhance the perception of passive haptic stimulus. Thus, we recommend creating a beautiful environment and a pleasant atmosphere. To do so, we suggest placing importance on the following entities, in accordance with our results and related work: high realism of objects [28], natural setting [16, 23, 78], bright colours and light [12].

Although studies regarding meditation in VR have shown that offering visual cues provide focus and help users to feel more present [22], we found that providing too much visual and auditive feedback can even decrease mindfulness. For example, moving animals can distract users from focusing on themselves. Our findings also showed that the simpler the VE, the faster people familiarise themselves with their surroundings. This ties back to the recommendation of offering an iterative procedure to familiarise oneself with every part of the surroundings. It is in line with previous

work, showing that the less mentally demanding a task is, the more participants focus on the most minor details [57].

Moreover, some participants reported that they decided against closing their eyes, although it might have helped with their mindfulness exercises because they feared missing out on some of the visual experience. As VR has been proven beneficial for meditation even with closed eyes [21, 47], we hypothesise this was due to our rich VE. Thus, if the surrounding is visually pleasing but simple enough, this would empower users to choose if they want to keep their eyes open or closed. On another note, the voice guiding the mindfulness exercise was mostly ignored or completely blanked out after some time. In this regard, we suggest the premise, 'introduction above implementation', which means that initial guidance benefits mindfulness, but afterwards, it can be perceived as a disruptive factor.

Recommendation 2: Virtual environments for mindfulness practice designed in aesthetically pleasing but simple ways may improve sensory fidelity, involvement, and subjectively experienced relaxation.

6.3 Passive Haptic Feedback

The majority of participants enjoyed the haptic experience. As indicated by the preferred conditions, those with grass were rated better overall, while footstep sound had less influence on the selection. During the apple-picking task, participants commented on being able to feel the seam between grass and wooden floor when entering and leaving the hut, i.e. when the visually perceived ground also changed. Our results show that, during the mindfulness task, the haptic experience (e.g. feeling the grass) became more important, increasing presence. Results of the IPQ support this impression, as its sub-scales show that tactile feedback independent of footstep sound has a significant effect on perceived presence, physically feeling present in the VE, and attention dedicated to the VE. Our data suggest several reasons for this development. First, our study setup was reduced to sitting or laying down during the mindfulness exercise, with no other task than to be mindful and relax. Removing distractions (i.e. no counting and manipulation of objects) shifted the focus to other entities such as the ground. Second, as known from the sensory homunculus, which is based on numerous studies conducted on the human brain by Penfield and Boldrey [52], higher sensory processing capacity is dedicated to the hands and fingers compared to the feet. As most participants reported touching the grass with their hands only during the mindfulness exercise, the stimulus would be higher during that part of the study. Further, participants wore socks and try-on-socks on top to attach the sensor. Thus their feet were less exposed to the ground. One could have increased haptic feedback intensity during this task by removing the socks altogether, however, due to hygienic standards, this was impossible in our setup. Third, this development might be due to successful mindfulness practice. By being more mindful, participants focused on what their bodies felt by consciously directing their attention. Thus, we hypothesise that mindfulness positively correlates with haptics.

However, we also found evidence that the other way is true as well: the haptic experience enriches mindfulness practice, thus the other way around. In contrast to previous assumptions, stroking the grass does not increase the focus on the VE but on the self.

Participants reported that it helped them to focus and that feeling the grass supported them in feeling and being aware of themselves. This assumption is supported by significant findings of the SMS. Its sub-scale *Body* shows a significant main effect for TACTILE FEEDBACK ($p = .001$), which shows that passive haptics significantly supported participants in perceiving physical sensations and to perceive themselves. Further, *Mind* showed a significant interaction effect between $G : NF$ and $NG : NF$. This further highlights the importance of tactile feedback for calming the mind. Thus, even a small item or object offering passive haptic feedback is potentially more beneficial than no haptic feedback at all. On that note, we also assume that material properties made a difference in mindfulness. Our results suggest that the grass' warmth and cosiness, in contrast to the cold and hard linoleum flooring, made a difference. However, a matching representation of the visual display and the haptic experience was essential for presence, and generally considered equally important by participants. One should test, though, how consistent textures must be to be convincing in VR. This is in line with work from Degraen et al. [19], investigating substitution possibilities for textures in VR.

Recommendation 3: Virtual environments for mindfulness practice should incorporate passive haptic feedback that matches virtual visual experiences.

6.4 Unobtrusive Ambient Sound Without Footstep Sound

Besides vision and tactition, audition was the third modality that we specifically addressed in our study. Participants agreed that ambient sound increased presence and relaxation. This is reflected by the significant WSPQ sub-scale sensory fidelity, which includes auditive aspects ($p=0.023$), although this sub-scale does not differentiate between effects of visual, auditive and haptic elements. Looking at our qualitative data, the effect of audition on mindfulness is not as homogeneous, though. For some, ambient sound was one factor creating a comprehensive experience, a nice atmosphere, that facilitated mindfulness practice. Others reported that they struggled with remaining focused on themselves because they felt their mind wander due to environmental sounds.

Further, auditive feedback in form of footstep sound does neither increase nor decrease presence and mindfulness. This is evidenced by results of the SMS, IPQ and WSPQ. The only exception is the WSPQ sub-scale *Sensory Fidelity* ($p = .013$). Here, it is shown that footstep sound positively impacts the perceived responsiveness of VR. Although the comparison to other subscales supports the conclusion that TACTILE FEEDBACK is the decisive factor, we cannot fully deduce that footstep sound never contributes to presence and mindfulness. However, step sound was not the decisive factor when rating the preferred condition, and qualitative and quantitative data showed that footstep sound on grass compared to footstep sound on wooden flooring is perceived as less relevant for presence. This might be because sounds are naturally more subdued on grass due to grass' natural material properties. Because also the walking habits changed due to wearing sensors, we conclude that footstep sound measured from ESP sensors used on grassy ground should not be added. This might change, however, if used on different flooring material and in a different setting, e.g. when sneaking [26] or when being in an urban setting [63].

Recommendation 4: Virtual environments for mindfulness practice should include unobtrusive ambient sound that matches the overall setting.

6.5 Limitations

As a limitation, we acknowledge our small sample size ($N=12$), although it still reflects the standard in HCI research [11]. However, our results are in line with prior works highlighting the benefit of haptic feedback for presence [42] and emotional responses [30, 45]. Thus, we extend those findings to mindfulness practice. Still, more research is needed to re-assess our assumptions due to the limitation of sample size and of investigating only the passive haptic feedback of grass and linoleum. Additionally, our study design offered a lot of freedom for the participant, i.e. the choice to hold the one controller in their hands vs. feeling the grass as well as opening vs. closing the eyes, which may have affected our results. However, we believe that the benefits of guaranteeing autonomy as a psychological need [61] enabled us to derive more in-depth insights that inform future design, as can be seen e.g. in design recommendation 1 (see subsection 6.1). Further, nine participants did not have any knowledge of mindfulness, three had minor knowledge from single teaching sessions or reading about it. Thus, our findings could change when repeated with mindful experts.

7 CONCLUSION

In this paper, we explored the impact of tactile (passive haptics through grass ground) and auditory (footstep sounds) feedback on presence and mindfulness. Quantitative and qualitative results of a user study ($N=12$) showed that tactile feedback significantly increases presence and supports mindfulness practice by improving the focus on the self. Based on our data, we derived five design recommendations for VR apps supporting mindfulness practice. We found that the study design should focus on iterations to support psychological need fulfilment. Also, VEs should be designed in an aesthetically pleasing way but still be simple enough to not distract from mindfulness exercises. Finally, passive haptic feedback and unobtrusive ambient sound can be beneficial for facilitating mindfulness and presence in VEs.

Based on our findings, we identify opportunities for future work. Besides involving mindfulness experts, it will be fascinating to investigate the relationship of less common modalities [4], especially olfaction and thermoception, and their interplay with presence and mindfulness. Though participants assumed a positive relation between such modalities and mindfulness, adding them could also contradict the derived theme of simplicity. As a starting point, we refer to the overview by Hürst et al. [27], as well as work by Maggioni et al. [41] for olfactory, Sheehan et al. [69] for thermoception, and Obrist [50] for gustatory implementation possibilities for VR. We hope that this paper will inspire further inquiry into how the interplay of different modalities in VR can support mindfulness practice and eventually increases the well-being of users.

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