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# Challenges and Opportunities of Immersive Technologies for Mindfulness Meditation: A Systematic Review

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Mindfulness is considered an important factor of an individual's subjective well-being. Consequently, Human-Computer Interaction (HCI) has investigated approaches that strengthen mindfulness, i.e., by inventing multimedia technologies to support mindfulness meditation. These approaches often use smartphones, tablets, or consumer-grade desktop systems to allow everyday usage in users' private lives or in the scope of organized therapies. Virtual, Augmented, and Mixed Reality (VR, AR, MR; in short: XR) significantly extend the design space for such approaches. XR covers a wide range of potential sensory stimulation, perceptive and cognitive manipulations, content presentation, interaction, and agency. These facilities are linked to typical XR-specific perceptions that are conceptually closely related to mindfulness research, such as (virtual) presence and (virtual) embodiment. However, a successful exploitation of XR that strengthens mindfulness requires a systematic analysis of the potential interrelation and influencing mechanisms between XR technology, its properties, factors, and phenomena and existing models and theories of the construct of mindfulness. This article reports such a systematic analysis of XR-related research from HCI and life sciences to determine the extent to which existing research frameworks on HCI and mindfulness can be applied to XR technologies, the potential of XR technologies to support mindfulness, and open research gaps. Fifty papers of ACM Digital Library and National Institutes of Health's National Library of Medicine (PubMed) with and without empirical efficacy evaluation were included in our analysis. The results reveal that at the current time, empirical research on XR-based mindfulness support mainly focuses on therapy and therapeutic outcomes. Furthermore, most of the currently investigated XR-supported mindfulness interactions are limited to vocally guided meditations within nature-inspired virtual environments. While an analysis of empirical research on those systems did not reveal differences in mindfulness compared to non-mediated mindfulness practices, various design proposals illustrate that XR has the potential to provide interactive and body-based innovations for mindfulness practice. We propose a structured approach for future work to specify and further explore the potential of XR as mindfulness-support. The resulting framework provides design guidelines for XR-based mindfulness support based on the elements and psychological mechanisms of XR interactions.

**Keywords: virtual reality, augmented reality, mindfulness, XR, meditation**

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# 1. INTRODUCTION

"Meditation is not an escape. It is the courage to look at reality with mindfulness and concentration. Meditation is essential for our survival"—Hanh (2013), p. 121

Mindfulness and mindfulness meditation provide a counterbalance to an increasingly busy everyday life in a digitalized world, in accordance with a promise of improved mental and physical well-being. Mindfulness, "the awareness that emerges through paying attention on purpose, in the present moment, and non-judgementally to the unfolding of experience moment by moment" (Kabat-Zinn, 2003, p. 145) has, among other things, been shown to increase happiness, work satisfaction, sense of meaning, sleep quality, and symptoms of chronic pain. In addition, it provides a positive effect on cognitive abilities such as attention span, creativity or problem solving. Over the past decades, these positive effects of mindfulness have led to an increased incorporation of mindfulness practice into everyday life. A number of digital tools aiming to increase or support mindfulness have been launched to accompany this trend. Consequently, more and more research on human-computer interaction (HCI) has addressed the topic of digitally mediated mindfulness practice.

Derived from a review of HCI literature, Terzimehić et al. (2019) set up a framework for the classification of HCI research in the mindfulness context. Further, some models and frameworks exist, which define guidelines for the design of digital mindfulness support (e.g., Salehzadeh Niksirat et al., 2017; Zhu et al., 2017). While those frameworks and models mainly focus on digital mindfulness practice via smartphone apps or wearables, in recent years, researchers have addressed the question of whether Virtual (VR), Augmented (AR), or Mixed (MR) Reality (in short: XR) can positively support mindfulness practice to a greater extent. Particularly, VR provides promising characteristics that might support mindfulness and related health and well-being. For example, VR headsets offer advantages in shielding external distractors (inclusivity, Slater and Wilbur, 1997). Peripheral visual cues in XR settings further enable guiding the user's focus in a more subtle way than audio-only meditation instructions or small-screen visual guides. Further, XR provides possibilities to foster bodily or mental states (e.g., showing biofeedback). However, either embodying a virtual avatar or not having any visual body reference might distract the user from their physical body and self-focus (Khoury et al., 2017). Thus, XR experiences need to be carefully designed to ensure focus, rather than creating new distractions through overly complex designs.

In other research fields, the specific characteristics of XR have been connected to various dimensions of behavior and concrete paths of impact in XR based interventions have been analyzed (Wienrich et al., 2020). In the field of mindfulness and mindfulness related outcomes of health and well-being such analyses are lacking. Thus, the present paper systematically reviews the literature on XR-based mindfulness support to determine whether current XR systems meet the requirements for mindfulness practice and to what extent they facilitate mindfulness states. We show which aspects of mindfulness are addressed in current research and identify gaps in the research. Finally, we propose a framework combining guidelines for digital mindfulness support with XR-specific design elements and impact paths.

# 2. RELATED WORK

## 2.1. Definitions of Mindfulness

### 2.1.1. Mindfulness: From Eastern Philosophy to Psychological Research

Mindfulness is a multifaceted term, originated in the eastern, Buddhist philosophies, which, originated in the research of Kabat-Zinn (2003), has found increasing influence in western psychological research. The definition of mindfulness varies across disciplines and can be divided into a number of different research paths. A broad overview of possible mindfulness definitions is provided by Khoury et al. (2017), who discuss and compare Buddhist and western definitions of the term. Roughly summarized, traditional Buddhist philosophers emphasize the practitioner's focus on the here and now and place it in a context of ethical and moral guidelines (Khoury et al., 2017). Western research is based on these Buddhist ideas. Thus, the term mindfulness in western definitions is characterized by focus on current sensations and the present moment (Brown and Ryan, 2003; Kabat-Zinn, 2003; Baer et al., 2008). Regarding the operationalization of mindfulness, western research is characterized by Kabat-Zinn (2003), who dealt with the therapeutic effects of meditation and introduced a program of *mindfulness-based stress reduction* (MBSR), which has grown quite popular in psychological research. Another commonly used definition in western research is that of Walsh and Shapiro (2006). Here, the focus is not on the state of mindfulness, but rather on the connection between (eastern) mindfulness-inducing practices, e.g., meditation, and (western) psychological research. In this context, a clear difference between the two branches of mindfulness definitions becomes apparent. While Buddhist definitions tend to emphasize the intensive and daily meditative practice and growing awareness and mindfulness in daily life, western mindfulness research tends to focus on positive side effects of mindfulness, such as stress reduction (Kabat-Zinn, 2003) or other therapeutic goals (Khoury et al., 2017).

### 2.1.2. Mindfulness in Human-Computer Interaction

In the past decade, beyond psychological research, the field of HCI has opened up to the topic of mindfulness. For example, Derthick (2014) presented an overview of the literature on meditation practice and technology use. Also Salehzadeh Niksirat et al. (2017) and Barton et al. (2020) dealt with the influence of interactive technologies on mindfulness meditation. Similar to psychology, HCI researchers define mindfulness as a mental state of experiencing of the present moment, while the most frequently cited constructs with respect to mindfulness are increased *attention*, *presence*, experience of *body sensations*, as well as a state of *non-judgment*, *moment-to-moment awareness*, and *meditation/MBSR* (Terzimehić et al., 2019).

Additionally to the division into mindfulness as a mental state and mindfulness-inducing practices such as meditation, Brown and Ryan (2003) further suggest a division into state and trait mindfulness. This division enables to make a distinction between a general, longer-lasting predisposition to mindfulness, and a more short-term effect of individual mindfulness exercises. Terzimehić et al. (2019) presented a detailed review on HCI and mindfulness, in which they analyzed and clustered 38 articles according to their definition of mindfulness, the applied mindfulness practice, the investigated technologies used to support mindfulness, and the evaluation and recording of mindfulness. Derived from their results, they set up a framework for the classification of HCI research in the mindfulness context. This framework includes various dimensions that shape their definition of HCI mindfulness research: The *role of mindfulness* as main goal vs. mediator for other mental states, the *type of practice* such as formal meditation or informal integration of mindfulness in everyday life, the focused *co-aspects of mindfulness*, and the associated *line of research*.

In accordance with the most commonly used definitions of mindfulness in HCI, this paper addresses mindfulness as a mental state of awareness toward the current moment and sensations. On the other hand we take into account being mindful as a trait as supposed by Brown and Ryan (2003). While in HCI mindfulness research meditation often is equated with mindfulness (Terzimehić et al., 2019), we distinguish between mindfulness as a mental state or trait and meditation as a conscious practice to reach this state. Finally, we differentiate between direct outcomes of mindfulness practice, such as concentration or focus, and indirect outcomes, such as therapeutic aims.

## 2.2. Guidelines for Digital Mindfulness Support

### 2.2.1. Digital Mindfulness Support Should Provide the Feeling of *Presence-In*

Over the last couple of years a few researches have tried to build up guidelines and frameworks for the design of digital mindfulness support. Zhu et al. (2017) presented a model which addressed and clustered types of digital mindfulness support. The resulting concept includes four successive stages of digital mindfulness support: *digitized mindfulness*, *personalized mindfulness*, *quantified mindfulness*, and systems providing *presence-in and presence-with*. The first three stages they presented are all characterized by what they call *presence-through*, thus, by tools designed to provide mindfulness support. They emphasize that most of the digital mindfulness support provides a digitized form of guided meditations or mindfulness tasks, where the human teachers or meditation partners are replaced by apps or audio books (stage one). The second stage, personalized mindfulness goes beyond this simple digitization and provides *personalized mindfulness* programs, e.g., by adjusting the provided content to user preferences or demographics. The *quantified mindfulness* in the third stage feeds back the user's physiological states during mindfulness tasks in the form of adaptive performance and meditation progress. While these tools provide information about mindfulness-"performance," they are based on judging the user which contrasts the definition of mindfulness as a state of non-judgment. Zhu et al. (2017) suggest, that digital mindfulness support should be rather used to design an aesthetic background for mindful interaction, inviting to further reflect the current moment(*presence-in and presence-with*). In an analogy to nature, digital mindfulness support should invite the user to feel co-present with objects or present within a natural or digital environment that by itself provides sources for mindfulness.

### 2.2.2. Digital Mindfulness Support Should Include Interaction and Feedback

Similar to the criticism of Zhu et al. (2017) on digitized mindfulness, Salehzadeh Niksirat et al. (2017) highlighted that presenting auditory guided meditation is not sufficient for successful digital mindfulness support. They developed a framework for smartphone-based mindfulness interactions which follows two psychological models on mindfulness interaction, Relaxation Response (Benson and Klipper, 1975) and Attention Restoration Theory (Kaplan, 1995). Relaxation Response derives from the basic idea that mindful interactions should include slowness and repetitiveness. Attention Restoration Theory further provides guidelines for the presentation of feedback during a mindful interaction. The authors suggest that "tired cognitive patterns" should be avoided, i.e., well-known melodies or motifs. They too stress that the information presented should not evoke judgment. In addition, they suggest using simple and "soft" feedback. In summary, Salehzadeh Niksirat et al. (2017) emphasize the importance of active interactions for digital mindfulness support and provide examples for its design.

### 2.2.3. Digital Mindfulness Support Should Be Body Based

One important aspect that plays a central role in the work of Khoury et al. (2017) on embodied mindfulness as well as in the HCI research of mindfulness is the physical body. Besides being present in the moment, Buddhist mindfulness practice includes: body, feelings, mind, and phenomena (four establishments of mindfulness; Khoury et al., 2017). The body is essential in mindfulness practice, which in turn leads to an improved body-mind connection. So-called body-scan meditations, mindful walks, or autogenic training, which are often part of MBSR programs direct the attention toward the body. The resulting body awareness of such exercises is closely related to mindfulness (Heeter, 2016; Khoury et al., 2017). These approaches are grounded in the psychological concept of embodied cognition, which implies the interrelation of body and mind and the importance of body perceptions in cognitive processes (Wilson, 2002). Thus, as all mental states are based on body perceptions, the state of mindfulness as well must be body based. Niksirat et al. (2019) adopted the concept of embodied cognition to expand the framework of Salehzadeh Niksirat et al. (2017). The resulting framework includes the detection of body movements in order to assess the user's state of mindfulness, an assistance in self regulation via slow and continuous interactions, as suggested in Benson and Klipper (1975) and a variety of feedback to add to the state of mindfulness.

## 2.3. Immersive Media and Mindfulness

Over the last decade, interactions with XR technologies have attracted increasing attention in mindfulness-related research. Growing numbers of studies have been published that include XR tools or interactions that aim to increase mindfulness. XR is an umbrella term that summarizes a variety of immersive technologies that provide computer-generated virtual objects, humans, or environments, and are characterized by a combination of real and virtual elements. The term is related to the reality-virtuality continuum of Milgram et al. (1995) and includes Virtual Reality (VR), Augmented Reality (AR), and Mixed reality (MR). In this paper, we use the terms XR or immersive media to reference immersive technologies in general. We use the term VR for systems that completely mask the physical world, and the term AR for systems that combine elements of the physical and virtual worlds. Human-XR-interaction is a segment of HCI research that deals with the perception and behavior of people in XR systems. While the work of Terzimehić et al. (2019) gives a broad insight into HCI-based mindfulness, they only include few XR-related research. Similarly, it remains unclear, whether the frameworks on digital mindfulness mentioned above are applicable for XR and whether XR interactions have the potential to match the criteria for mindfulness support.

### 2.3.1. Guidelines on XR-Based Mindfulness Support

While the above-mentioned frameworks are not specifically bound to XR interactions, Roo et al. (2017) developed a set of guidelines to support the design of XR-based mindfulness support. However, the proposed guidelines are closely related to those of Zhu et al. (2017) or Niksirat et al. (2019), with only a few guidelines specifically addressing XR-related design challenges. They too emphasize the importance of subtle guidance, while on the other side proposing the idea of challenging the user's focus via subtle distractors to train their ability to concentrate (distraction vs. guidance). In accordance with the idea of avoiding complex, judgment-provoking stimuli in mobile-based mindfulness interaction (Salehzadeh Niksirat et al., 2017; Niksirat et al., 2019), they stress that virtual environments in XR-based mindfulness support should be kept minimal and contribute to non-judgment. Also, similarly to the more general guidelines, they highlight that XR-based mindfulness support should avoid quantified performance feedback. They further address the idea of promoting acceptance via events that are out of the user's control and promoting autonomy by only including ambient information or feedback and allowing for exploration. The two guidelines of Roo et al. (2017) that apply most specifically to XR design are *using tangible interaction* and *choosing the right reality*. In order to ensure the focus on the user's own body they promote tangible interactions and haptic feedback. Additionally, they emphasize the importance of taking into account the user's personal traits concerning the perception of XR, for example the ability to distinguish reality and virtuality (suspension of disbelief, Heeter, 1992) or the tendency to suffer from simulation sickness.

### 2.3.2. Framework for XR Intervention Evaluation

Within other research topics, it has been shown that XR interactions can have a broad impact on human experience and behavior [e.g., anxiety therapy (Morina et al., 2015), discrimination experiences (Peck et al., 2013), involvement with nature (Ahn et al., 2016)]. Wienrich et al. (2020) presented a framework, *BehaveFIT*, that describes direct and indirect influences of VR interactions on human perceptions and behavior. They suggested three stages of influence: the presented content (*XR elements*), the corresponding perceptions and reactions, and the indirectly influenced attitudes and behavior decisions. They define VR via *virtual environment*, *virtual objects*, *virtual others*, and *virtual self-representation*. The XR elements subsume the visual, aural, or haptic execution, their behavior without the user's input, and the interactivity and reactions to user movements or actions. The corresponding perceptions on the other hand include the user's direct responses to these contents which on the one hand might include *XR-specific perceptions*, such as *sense of presence* (section 2.3.3) or *sense of embodiment* (section 2.3.6), and behavior-related perceptions and mental states, such as sense of space or time and current affects. Wienrich et al. (2020) emphasize the importance of including XR-specific perceptions into the analysis of XR-based influences on human perceptions and behavior in order to fully understand the mechanisms of XR interactions on psychological outcome variables. Finally, they address the influence of *individual characteristics* as well as *physical intervention settings* on the effect of XR interventions. Consequently, their framework offers a systematic description of immersive interventions that might also be important for XR-based mindfulness support. In the following we discussion immersion *per se*, as well as the four XR elements suggested by Wienrich et al. (2020) concerning their potential for XR-based mindfulness support.

### 2.3.3. Immersion and Presence

XR in general, and VR specifically, integrate well into the concept of digital mindfulness support by presence-with/presence-in (Zhu et al., 2017), particularly considering the concept of presence as the main defining characteristic of VR-specific perception. Conceptually, the virtual *sense of presence* describes a subjective state (Slater, 1999) which can be further separated into dimensions such as *place illusion*, and *plausibility illusion* (Skarbez et al., 2018) while the term *immersion* defines the "extent to which the computer displays are capable of delivering an inclusive, extensive, surrounding and vivid illusion of reality to the senses of a human participant" (Slater and Wilbur, 1997). In order to create immersion in a virtual environment, the medium should shield the user from their physical environment, the user's actions should lead to consequences in the virtual environment and, ideally, an immersive system should provide sensual information for different perception modalities (Slater, 1999). We consider immersion as a basic requirement for XR interactions. As it based on technical requirements, it is listed separately to the XR elements which refer to the provided content within an immersive system. Our analysis focuses on the content of XR-based mindfulness support. Thus, while we do acknowledge immersion as one potential of XR and refer to it in the effect synthesis, it is not included in our analysis of XR elements.

### 2.3.4. Virtual Environments

In an interview with mindfulness experts, Navarro-Haro et al. (2017) discovered, that imitations of nature might help experiencing mindfulness. On the other hand, abstract shapes can provide the possibility of exploring a meditative state (Du Plessis, 2017). Virtual environments provide a broad field of possibilities to create different emotional frames for a mindfulness experience. They can be visualized as naturalistic or artificial, provide abstract or figural backgrounds, and be enhanced by providing background sounds or haptic stimuli such as wind. Thus, as long as the foundations for immersion and thus presence are set, designing a virtual environment as a background for mindfulness support provides a variety of possibilities. Overall, the virtual environment can set the background for presence-in (Zhu et al., 2017) or exploration (Roo et al., 2017).

Within a virtual environment, XR offers a broad range of possibilities to design feedback in a subtle, subconscious way. As Zhu et al. (2017) and Salehzadeh Niksirat et al. (2017) suggest, (bio-)feedback should not be provided as a measure to quantify mindfulness but rather to design a meaningful background for mindful interactions. XR based mindfulness support give the opportunity to follow these instructions, e.g., by providing feedback peripherally or by creating ever-changing environments that adapt seamlessly to their current needs or states (e.g., Roo et al., 2017). However, it has not been systematically examined how virtual environments are designed in current research on XR-based mindfulness support, influence of different interpretations of feedback in XR on mindfulness and how they affect the state of mindfulness achieved by XR-supported mindfulness practice.

### 2.3.5. Virtual Objects

Even most simple virtual environments provide some kind of interactivity, such as visual movement information in the opposite direction to users' head movements, or tracking of gestures or body movements. Virtual objects create a new design space which offers a variety of possibilities and freedom in interaction design (Wienrich et al., 2017). Thus, the user might find new and curiosity arousing ways of interacting with objects. Further, as stated by Zhu et al. (2017) or Roo et al. (2017), tangible objects might be helpful in order to keep the focus on the user and their body while exploring a virtual environment. Thus, due to the diversity of virtual objects and interactions, they can easily be adapted to different guidelines of mindful interactivity. However, it remains open, how the possibilities of interactions with virtual objects are applied in current literature.

### 2.3.6. Virtual Self-Representation

Next to biofeedback within virtual environments and tangible object interactions, HCI offers interesting new ways to support full-body experiences outside of traditional yoga practice, mindful walks or body scan meditation. For example, Ståhl et al. (2016) introduced a full-body heat stimulation to subtly guide attention toward specific body parts without audio guidance. Further, (Niksirat et al., 2019) presented a digitally supported system for kinetic mindfulness practice, including movement tracking and smartphone-based feedback.

Within the field of XR, applications including a virtual self-representation offer much potential for body-related experiences. Similarly to the concept of immersion and presence, we distinguish between virtual self-representation as a visual, aural, and/or haptic depiction of the user within an XR system (avatar) and the subjective sense of embodiment as the corresponding XR-specific perception (Wienrich et al., 2020). As mentioned above, in mindfulness research the term *embodiment* or *embodied cognition* refers to the grounding of all experiences and feelings in the physical body (Wilson, 2002; Khoury et al., 2017). XR research adopts this concept and furthers it by introducing the *sense of embodiment* (Kilteni et al., 2012) or *virtual embodiment* (Roth and Latoschik, 2020), which describes the "conscious experience of self-identification (body ownership), controlling one's own body movements (agency), and being located at the position of one's body in [a virtual] environment (self-location)" (Roth and Latoschik, 2020). XR-based mindfulness support should carefully avoid interrupting the connection between the user and their body (Roo et al., 2017). Embodying a virtual self-representation within the virtual environment can help strengthen (Tajadura-Jiménez et al., 2012) or modify (Llobera et al., 2013) body perceptions and awareness. Consequently, the virtual self-representation leads to implications for the perception of the physical body (see Ratan et al., 2020 for an overview of the so called *Proteus effect*). While virtual self-representations thus provide the potential to include the body in an XR-based mindfulness support, it has not been analyzed systematically to what extent they are part of current research or how they impact on mindfulness.

### 2.3.7. Virtual Others

The representation of virtual others is comparable to the virtual self-representation. Virtual others can either represent other users of the XR system (avatars) or represent artificial interaction (agents). Interactions with virtual others can create social context and lead to an XR-specific perception, social presence (De Kort et al., 2007). The guidelines for digital mindfulness support mentioned above do not address interactions with other users. Nonetheless, the involvement of virtual others can be an opportunity, e.g., by using virtual agents as a reference for mindful behavior or by creating mindfulness-supporting interactions with other users. Here too, it has not yet been analyzed, whether and how virtual others are included in current XR-based mindfulness support and correspondingly whether impacts on mindfulness.

## 2.4. Outline of the Review

The topic of mindfulness has gained considerable attention in HCI research over the past decade. Various aspects of mindfulness and corresponding concepts have already been researched and summarized in this field. Terzimehić et al. (2019) provide an overview of how mindfulness is treated in HCI and which aspects of mindfulness are particularly emphasized in HCI research. While they mention XR interaction in their work, so far there does not exist a comprehensive overview of which aspects of mindfulness are already part of XR research.

Additionally, several authors so far have presented frameworks and guidelines toward creating digitally enhanced mindful interactions. XR systems offer many opportunities to meet those guidelines via the visual design, multimodal representation, and interactivity of the provided virtual environment, virtual objects, virtual self-representation or virtual others. Roo et al. (2017) listed a number of guidelines, which they applied to the design of XR-based mindfulness support. However, there has been no systematic research on the design of XR-based mindfulness support in current research and whether it meets those guidelines. Finally, it has not yet been summarized what effect different variations XR and its corresponding perceptions have on mindfulness. The current work bridges those research gaps by presenting the results of an analysis of the currently available literature on XR-based mindfulness support. The following research questions are addressed:

(I) What are the differences in the research of XR-based mindfulness support compared to the broader field of HCI mindfulness research?
(II) Which XR elements are used in current research on XR-based mindfulness support and do they meet the guidelines for digital mindfulness support?
(III) Which type of guidance, feedback, and tasks are included in current XR-based mindfulness support and do they support embodied mindfulness?
(IV) What effect does the design of XR elements have on mindfulness according to current research?

To answer the research questions I–III, the only constraint for the selection of papers was that they described any XR system designed to increase mindfulness. The analysis in research question IV included only articles that assessed the impact of XR-based mindfulness support in a pre-post design, comparing at least two experimental groups and including a subjective mindfulness measure. We did not restrict our analysis to a specific population.

Finally, we aimed for a model that combines the more general model for XR intervention design and evaluation, *BehaveFIT* described by Wienrich et al. (2019) with guidelines for the design of digital and XR-based mindfulness support. It further addresses the identified research gaps derived from the results of the review.

## 3. METHODS

We performed a structured literature review in which we included full-papers as well as short-papers. To get an overview of XR-related work in both HCI and psychology, we used two databases for the search: ACM Digital Library and U.S. National Institutes of Health's National Library of Medicine (PubMed). To ensure the completeness of our results, we cross-checked the resulting papers with another data base, APA PsycInfo. This search did not reveal further articles compared to the results of the former two. The review was conducted in accordance with PRISMA (Moher et al., 2011).

### 3.1. Search and Extraction

The search term was built as follows. We only included papers published between January 2010 and October 2020, that included both mindfulness-related and XR-related terms in their title or abstract. We searched for the following term: ["mindfulness" OR "mindful" OR "meditation" OR "meditative"] AND ["virtual reality" OR "VR" OR "augmented reality" OR "AR" OR "mixed reality" OR "MR" OR "XR" OR "immersion" OR "immersive"]. We included meditation in the search term, as it was most commonly used as a synonym to mindfulness in HCI research (Terzimehić et al., 2019).

The screening process was carried out in accordance with PRISMA guidelines and is depicted in **Figure 1**. In the first step, we combined the search results of both databases and excluded all duplicates. To narrow down our results to papers that matched our research aims, we manually screened the abstracts and excluded papers that (a) did not focus on mindfulness or mindfulness meditation, (b) did not include an XR system, or (c) were assigned as reviews or meta-analyses. In the next step, we further screened the full-text articles and excluded papers, which (a) did not investigate the influence of XR on mindfulness or mindfulness meditation outcomes, or (b) did not focus on mindfulness or mindfulness meditation. The resulting papers were assigned to two categories based on whether they included an effectiveness study addressing the impact on mindfulness or mindfulness-related outcomes (further mentioned as EMPIRIC, **Figure 1**, green area, right) or presented a new design for an XR-based mindfulness support without evaluation of mindfulness or mindfulness-related outcomes (further mentioned as DESIGN, **Figure 1**, green area, left). The total of these papers were included in the analysis to answer research questions I–III.

To answer research question IV we set up a list of eligibility criteria in accordance with PICOS (Methley et al., 2014). We only analyzed the papers classified as EMPIRIC. We did not restrict the participants to a specific population (P). Concerning the intervention (I), we included only papers where the XR interaction aimed to increase mindfulness. We excluded papers that did not compare the XR interaction to either a control group, a group that performed a mindfulness-supporting interaction without XR, or a group that performed a different version of the XR interaction (C). As an outcome variable we narrowed down the results to papers that included a subjective mindfulness measure (O). Finally, we only included papers that included a pre-post comparison of mindfulness (**Figure 1**, gray area, left). For additional analysis on whether the sense of presence was related to subjective mindfulness, we added a second analysis with papers that (O) in a subjective mindfulness measure as well as a measure of presence or embodiment and calculated a correlation between the two measures (**Figure 1**, gray area, right).

### 3.2. Analysis

To answer research question I, we analyzed the papers according to the framework developed by Terzimehić et al. (2019) which includes five dimensions: *lines of research*, *role*

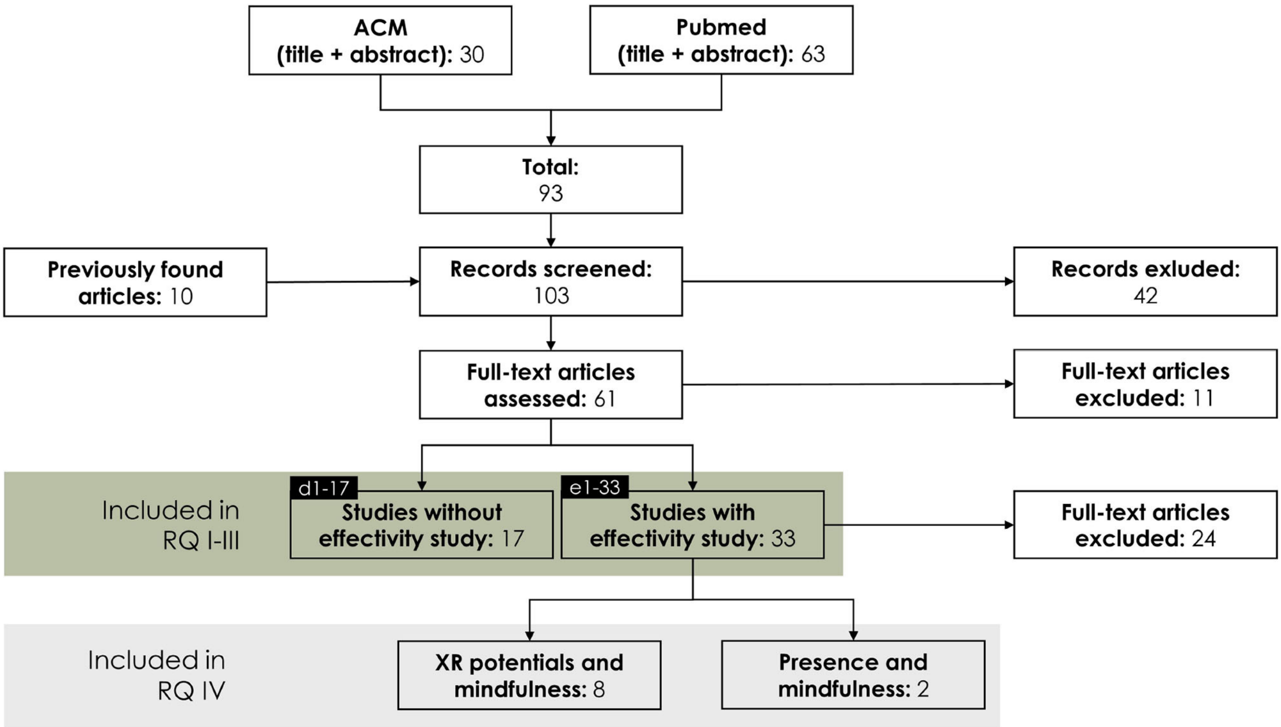


**FIGURE 1 |** Depiction of the PRISMA flow diagram (Moher et al., 2011). The chart shows the process of paper extraction. Fifty papers were included in the analysis of XR-based mindfulness support. Ten papers were included in the final effect synthesis.

*of mindfulness*, *type of mindfulness practice*, *longevity*, and *co-aspects of mindfulness*. Under the term *lines of research*, their framework divides mindfulness literature into research on meditation practice, therapy, mindfulness in interactions, reflection and knowledge gain, performance enhancement in other non-mindfulness-related tasks and meta-level research. *Role of mindfulness* divides research into papers that handle mindfulness as the goal of an interaction, as a way of being or as a mediator for other intervention outcomes, mainly used in therapy. The *type of mindfulness practice* can either be coded as formal, e.g., in guided meditations, or informal. In the dimension of *longevity*, research can be divided into papers that aim for short-term outcomes of XR-based mindfulness support and papers that aim for long-term changes in mindfulness. *Co-aspects of mindfulness*, addresses terms that frequently are used synonymous to mindfulness, such as meditation, reflection, therapy, or performance.

To answer research questions II, we relied on the work of Wienrich et al. (2020) and their framework of XR-based behavioral influences and divided the elements of XR (XR elements) into: *virtual environment*, *virtual objects*, *virtual self-representation*, and *virtual others*. For each of those categories, we analyzed whether the respective visual and non-visual representation, behavior and interactivity matched the criteria for mindful interactions. Based on the previous work on mindfulness interaction guidelines, we picked the following criteria. Concerning the virtual environments, we analyzed (a) the emotional framing, (b) the inclusion of figurative or abstract elements, (c) the visual clutter of the environment, (d) the visual detailedness of included elements, and (e) the usage of natural vs. human-made elements. For virtual objects, we analyzed whether they were instrumentalized, detailed, natural, or human-made and haptic or non-haptic. Concerning virtual self-representation and virtual others, we analyzed, whether they were humanoid or non-humanoid, full body representations or body parts, presented from 1st or 3rd person perspective, generic or personalized and interactive or non-interactive.

Concerning research question III we further analyzed whether the tasks and feedback used in the papers were in accordance with the guidelines of Salehzadeh Niksirat et al. (2017), Niksirat et al. (2019), and Roo et al. (2017) for interactive mindfulness tasks. We thus analyzed whether the systems (a) included body based interactivity, such as biofeedback or body movements, (b) included haptic or multi-modal feedback and guidance and (c) whether the feedback was presented peripherally and non-quantifiably. To prepare for the effect analysis, we further included the measured XR-specific perceptions (presence, embodiment, simulator sickness, or social presence).

For research question IV, we additionally included the specifications of the included independent variable, the subjective mindfulness measure and the measure of XR-specific perceptions. We then analyzed the results of these investigations on whether the tested conditions had an impact on (subjective) mindfulness, or whether the XR-specific perception was related to the subjective mindfulness measure.

## 4. RESULTS

The search within ACM Digital Library revealed 30 papers, duplicates excluded (PRISMA flow chart, **Figure 1**). The search within PubMed led to 63 articles, duplicates excluded. We added ten papers from our previous research that were not included in either of the databases or were published during the process of the review, leading to a total paper number of 103. Forty-two papers did not match our criteria and were thus excluded in the screening of abstracts. After screening the full-text articles of the remaining, we excluded eleven more papers. Further, we had to exclude one paper, which duplicated the data and results from another one leading to a number of $n = 50$ papers that were included in the analysis of research questions I–III. The split into EMPIRIC and DESIGN papers led to $n1 = 33$ EMPIRIC and $n2 = 17$ DESIGN papers. The further extraction of papers for research question IV led to a result of $n1 = 8$ papers that included a subjective mindfulness measure and $n2 = 2$ papers that included a comparison of mindfulness and subjective sense of presence.

As mentioned above, the following sections include both papers presenting XR-based mindfulness support systems or designs (DESIGN: $n = 17$) as well as papers that included an effectiveness study either on mindfulness or on therapeutic outcomes (EMPIRIC: $n = 33$). Within this section, the papers included in the review are referred to by an ID (EMPIRIC: e01–e23/ DESIGN: d01–d17) which relates to the result tables (**Table 1**). The results of our analyses are presented in **Table 2**, **Supplementary Tables 1–6**.

**TABLE 1** | List of paper abbreviations.

| ID | References | ID | References |
|---|---|---|---|
| d01 | Chen et al. (2018) | e01 | Lee and Kang (2020) |
| d02 | Zaharuddin et al. (2019) | e02 | Haisley et al. (2020) |
| d03 | Gromala et al. (2011) | e03 | Goldenhersch et al. (2020) |
| d04 | Damen and Van der Spek (2018) | e04 | Chavez et al. (2020) |
| d05 | Auccahuasi et al. (2019) | e05 | Kwon et al. (2020) |
| d06 | Moseley (2016) | e06 | Rice et al. (2018) |
| d07 | Pendse et al. (2016) | e07 | Kazzi et al. (2018) |
| d08 | Patibanda et al. (2017) | e08 | Botella et al. (2013) |
| d09 | Seol et al. (2017) | e09 | Gromala et al. (2015) |
| d10 | Potts et al. (2019) | e10 | Cheng et al. (2020) |
| d11 | Bruggeman and Wurster (2018) | e11 | Cikajlo et al. (2017) |
| d12 | Choo and May (2014) | e12 | Flores et al. (2018) |
| d13 | Du Plessis (2017) | e13 | Venuturupalli et al. (2019) |
| d14 | Prpa et al. (2018a) | e14 | Burton et al. (2013) |
| d15 | Song et al. (2019) | e15 | Navarro-Haro et al. (2019) |
| d16 | Moseley (2017) | e16 | Tarrant et al. (2018) |
| d17 | Kosunen et al. (2017) | e17 | Gomez et al. (2017) |
| | | e18 | Navarro-Haro et al. (2016) |
| | | e19 | Mistry et al. (2020) |
| | | e20 | Cebolla et al. (2019) |
| | | e21 | Prpa et al. (2018b) |
| | | e22 | Roo et al. (2017) |
| | | e23 | Paredes et al. (2018) |
| | | e24 | Chung et al. (2018) |
| | | e25 | Costa et al. (2020) |
| | | e26 | Tinga et al. (2019) |
| | | e27 | Salminen et al. (2018) |
| | | e28 | Min et al. (2020) |
| | | e29 | Costa et al. (2019) |
| | | e30 | Seabrook et al. (2020) |
| | | e31 | Navarro-Haro et al. (2017) |
| | | e32 | Kosunen et al. (2016) |
| | | e33 | Andersen et al. (2017) |

### 4.1. The Role of Mindfulness in XR Mindfulness Research

Compared with the dimensions of HCI mindfulness research (Terzimehić et al., 2019), current EMPIRIC XR mindfulness research uses a rather narrowed definition of mindfulness (**Table A1**). The majority of EMPIRIC papers explored XR-based mindfulness support as a means to support therapy for a variety of psychological and physical disorders. Within these papers, mindfulness was mainly considered a mediator for the decrease of symptoms such as anxiety (e04, e05, e11–e17), stress or arousal (e04, e07, e11, e12, e25), or pain (e02, e08, e09, e13). Further, it was treated as a mediator for the increase of sleep quality (e01), general psychological health in elderly care (e10), concentration (e06), and positive affective states (e17, e18, e19). Most of the investigations instead included an evaluation of the short-term outcomes of one interaction (e02, e04, e07, e09, e12, e13, e16–e18). Consistent with the subordinate role as mediator for therapeutic outcomes, some of the therapeutic papers did not include a mindfulness measure in their analysis (e01, e02, e04–e06, e08, e09, e12–e14, e17–e19) but only measured the expected symptom reduction.

Also in EMPIRIC papers that investigated healthy participants, mindfulness was mainly used as a mediator for stress reduction (e23–e26) but also for anxiety (e28) and compassion toward others (e27). The other papers concerning research on XR-based meditation practice treated mindfulness as the main goal (e29–e33). Here, too, the focus was rather on short-term than on long-term XR-mindfulness outcomes (e20–e30, e32, e33). In accordance with the narrowed lines of research, most of the EMPIRIC papers used mindfulness synonymously with meditation (e01, e02, e04, e05, e07–e11, e13, e19, e22, e25–e26, e30, e32, e33), or therapy (e03, e12, e14, e17, e18) rather than focusing on mindfulness *per se* (e06, e15, e16, e20, e21, e23, e27–e29).

Compared to the EMPIRIC papers, the DESIGN papers rather focused on mindful meditation practice (d09–d17) and self-reflection (d06–d08) than on therapy (d01–d05). Accordingly, mindfulness was almost evenly mentioned as the main goal

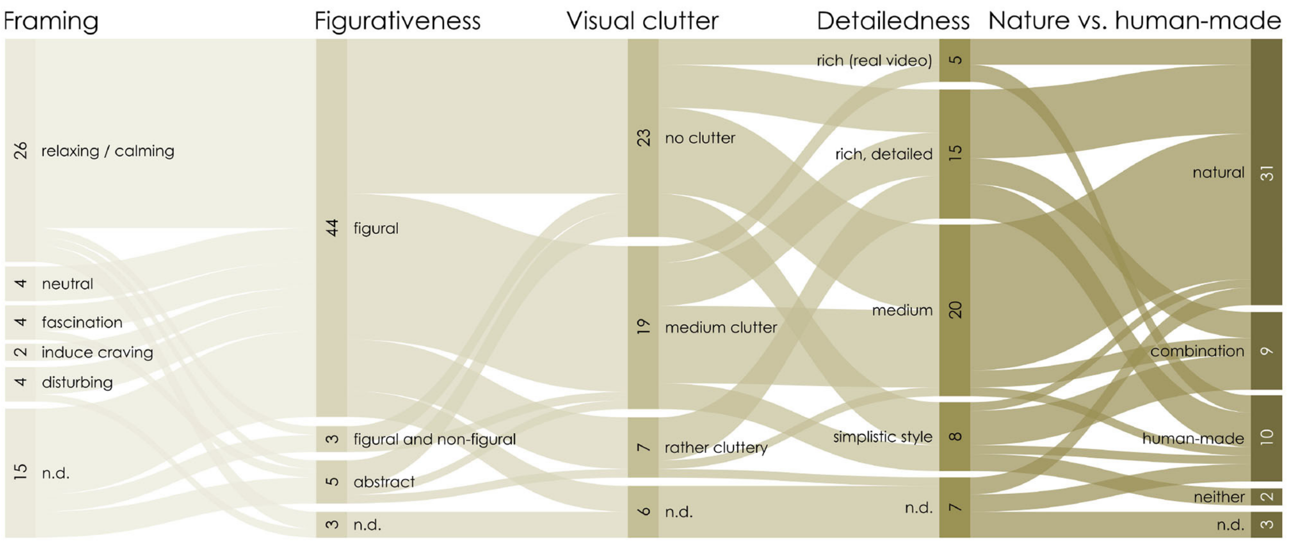


**FIGURE 2 |** Depiction of the different attributes of virtual environments used in the literature on XR-based mindfulness support. As some papers included different versions of virtual environments, the numbers here do not match the total number of papers.

(d06–d08, d13–d17) and as a mediator for other psychological or physical states (d01–d05, d09–d12). Additionally, two of the DESIGN papers focused on mindfulness in interaction (d09, d10).

## 4.2. The Role of XR-Elements in XR Mindfulness Research

Almost all of the EMPIRIC papers emphasized *immersion* as the most important property of XR-systems to support mindfulness. However, many of these papers did not specify, in which way immersion would be crucial for supporting mindfulness, e.g., whether the exclusion of external distractors, the surrounding nature of virtual environments or its vividness was the decisive factor. In the following sections, we describe how XR elements have been addressed in the current literature.

### 4.2.1. Types of Virtual Environments

The results of the analysis of virtual environments are depicted in **Supplementary Table 2** and **Figure 2**. The first factor we analyzed concerning the types of virtual environments used in current literature was the positive or negative framing of the experience. In most of the EMPIRIC papers, authors aimed for a relaxing, soothing, or generally calming environment (e1, e04, e06–e09, e11, e12, e15, e17, e18, e22, e23, e25–e29, e31, e33). The other EMPIRIC papers either aimed for a feeling of awe or fascination (e24) or did not define the framing of their environment (e02, e10, e13, e16, e19–e21, e30, e32). Four of the EMPIRIC papers included environments that aimed for negative framing. While e03 focused on the induction of craving via drug-related cues, e05, e06, and e14 included disturbing environments to contrast or challenge the user's mindfulness. In contrast to EMPIRIC papers, most of the DESIGN papers either described their environment neutrally or did not define the framing of the virtual experience (d03–d05, d08, d10, d13–d17). The DESIGN papers that described their environment as a possible framing either aimed for relaxing or calming effects (d02, d06, d11) or as well for the feeling of fascination and awe (d07, d12). The DESIGN papers as well did include environments to induce craving (d01) or anxiety (d09).

Concerning the general figurativeness of the environment, we analyzed whether the virtual environments in the literature included figurative and well-known patterns or objects or whether they relied on more abstract shapes. A majority of both EMPIRIC and DESIGN papers built their environments from figurative elements (e01–e06, e08, e10–e20, e22–e25, e27–e33; d01–d05, d07, d08, d10–d12, d17). While two papers included both figurative and non-figurative elements (fog) in their environments (e09, e21; d14), only five papers did not use any figurative elements (e24, e26; d13, d15, d16). Three of the papers did not include a detailed description of their environment (e07, d09) or did not define a specific environment but rather the possibility to build a variety of environments (d06).

Most of the EMPIRIC and DESIGN papers included environments, that either included only few elements or objects (e02, e03, e06, e08, e11, e20, e21, e23, e24, e26, e27, e29, e32, e33; d03, d05, d08, d10, d11, d14–d17) or included some more objects, but without inducing a high feeling of clutter (e04, e09, e11, e12, e13, e15, e17, e18, e19, e22, e23, e28, e30, e31; d02, d04, d07, d12, d13). Nevertheless, some of the EMPIRIC papers used rather cluttered environments, mostly on purpose, to contrast with more minimalistic environments or to induce an anxiety-related framing (e05, e06, e10, e11, e14, e16, e24).

While aiming for minimalism concerning the number of potential distractors within the environments, virtual environments in the EMPIRIC papers had a rich and detailed design (e04, e06, e09, e10, e16, e23, e24, e33), some of them using 360°-videos (e02, e03, e11, e20, e30), or at least had a medium amount of detail (e05, e06, e08, e11, e12, e15, e17–e19, e21, e22, e27, e29, e31). We rated only four of the EMPIRIC papers as simplistic and low-detailed (e13, e26, e28, e32). The virtual environments in DESIGN papers on the other hand were almost evenly rated as richly-detailed (d05, d11, d12, d13), medium detailed (d02-d04, d08, d14, d15), or simplistic (d01, d06, d09).

Finally, most of the EMPIRIC and DESIGN papers aimed for environments that were at least inspired by nature, including trees, water, beaches, grass, or mountains (e01, e02, e04, e08, e09, e11–e13, e15–e19, e21–e25, e29–e31; d02–d05, d08, d11, d14, d15). Only seven papers presented only human-made elements (e03, e05, e14, e20; d01, d10, d13). The other papers either included a combination of both nature-related and human-made elements (e06, e10, e27, e28, e32, e33; d07, d12, d17) or neither of them (e07, e26; d06, d09, d16).

In summary, the current literature predominantly uses positively framed, nature-inspired virtual environments. There is more emphasis on figuration, although there do exist some examples of how to design more abstract mindfulness-inducing environments. Additionally, our analysis shows that current literature uses predominantly non-cluttered environments that enable focus rather than challenging it. Nonetheless, the depicted virtual environments that are presented mostly are at least medium detailed rather than relying on simple shapes.

#### 4.2.2. Types of Virtual Objects

The analysis of the interactive virtual objects is depicted in **Supplementary Table 3**. Only five papers included virtual objects (e10, e22, e28; d09, d10). Except for e22, which presented an AR system where the users explored and shaped augmented sand, all of these papers used figurative objects. In accordance with the generally rather detailed virtual environments, most of the presented virtual objects were rather detailed (e10, e22, e28, d09). While some of the objects clearly worked as tools for mindfulness-inducing interactions, such as aroma-therapy (e10) or gardening (d10), the other objects rather served as a possibility to explore the object or the user's own physical state (e22, e28, d09). The virtual objects that aimed for exploration were augmented and did include haptic stimulation.

#### 4.2.3. Types of virtual Self-Representations

The analysis of virtual self-representations is depicted in **Supplementary Table 4**. Seven papers included a visual self-representation (e03, e20, e22, e28; d08, d09, d10). Except for d08, who designed a growing tree to represent the user, the self-representations were either designed as humanoid hands and arms (e03, e28, d09), perceived from first person perspective or a had full humanoid avatar, presented in first (d10) or third person perspective (e20, e22). While in e20 the users viewed themselves in a live video, the other papers did not use a personalized self-representation. Additionally, most of the virtual self-representations were responsive to the users actions, while some moved in accordance with the user's body movements (e20, e28; d09, d10), one of them grew and changed according to the user's current state (d08).

#### 4.2.4. Types of Virtual Others

The analysis of papers that included a virtual others is depicted in **Supplementary Table 5**. Seven papers included virtual others (e06, e11, e14, e27, e32; d05, d17). All of these were designed humanoid and included either body parts (d05), an upper body (e11) or a full humanoid body (e06, e11, e14, e27, e32). Some of the virtual others were only presented visually and did not enable interaction (e27, e32; d05, d17). The others represented real humans and included the possibility to interact either verbally or non-verbally (e06, e11, e14, e17).

### 4.3. Guidance, Feedback, and Interactivity

The result of our analysis of the included sensory modalities, the types of guidance, the types of mindfulness tasks, the used input devices, and the types of feedback is depicted in **Supplementary Table 6**.

#### 4.3.1. Inclusion of Multiple Sensory Modalities

As opposed to visual stimuli which were included in all papers, nine papers did not mention audio input either as background sounds or as verbal guidance (e14, e22, e23, e28; d05, d09, d10, d11, d15). The other papers mostly included visual and aural input, while five papers additionally included haptic (e20, e22, e28; d07, d09) or kinesthetic information (e10, e20, e22; d10).

#### 4.3.2. Types of Guidance

Concerning the guidance of the user's focus (**Figure 3**), a majority of papers relied on vocal instructions (e02–e13, e15–e20, e25–e27, e29–e33; d01, d02, d04, d08, d12, d13, d17). While only two papers included text-based visual instructions (e10, e11), some of the other papers included visual or aural cues for focus guidance (e13, e27, e32, d09, d17). The other papers either did not describe the type of focus guidance they used or presented the instructions before the XR experience rather than including it (e01, e14, e21–e24, e28; d03, d05–d07, d10, d11, d14–d16).

#### 4.3.3. Types of Mindfulness Tasks

The mindfulness-inducing tasks that were presented in the literature mostly included focusing the present moment. Some of those led the focus to the virtual environment (e08–e10, e12, e15–e18, e21–e24, e28–e32; d04, d14, d17). The papers that included tasks that led the focus to the user's body either included body scan meditations (e11, e32, d17, d05), the exploration of current sensations (e02, e08, e12, e15, e26, e30; d12, d15) or focus on breathing (e02, e08, e13, e25, e26, e29; d08, d11, d12). Only five papers included more active interactions within the virtual environment, either navigating through the environment (d02, d03, d04) or some kind of kinetic meditation (e20; d10).

#### 4.3.4. Types of User Input

As indicated by the more passive tasks presented in most of the papers, no active input from the user was required in most of the tasks. The papers which included user input and respective feedback mostly relied on biofeedback, which either based on respiration (e13, e21, e22, e26, e27; d08, d11, d12, d14, d15), neural activity (e27, e32; d06, d10, d12, d13, d15, d17), heart tracking (e22, e28, d09, d15), or skin conductance (e09, d13). Seven papers instead required body movements. Those were divided into hand gestures (e10, e22; d15), eye movements (d04, d16), and full body movements (e20; d03, d10). Finally, one paper included the voice as input medium (e08). Here, users navigated through the environment by telling the experimenter where to move.

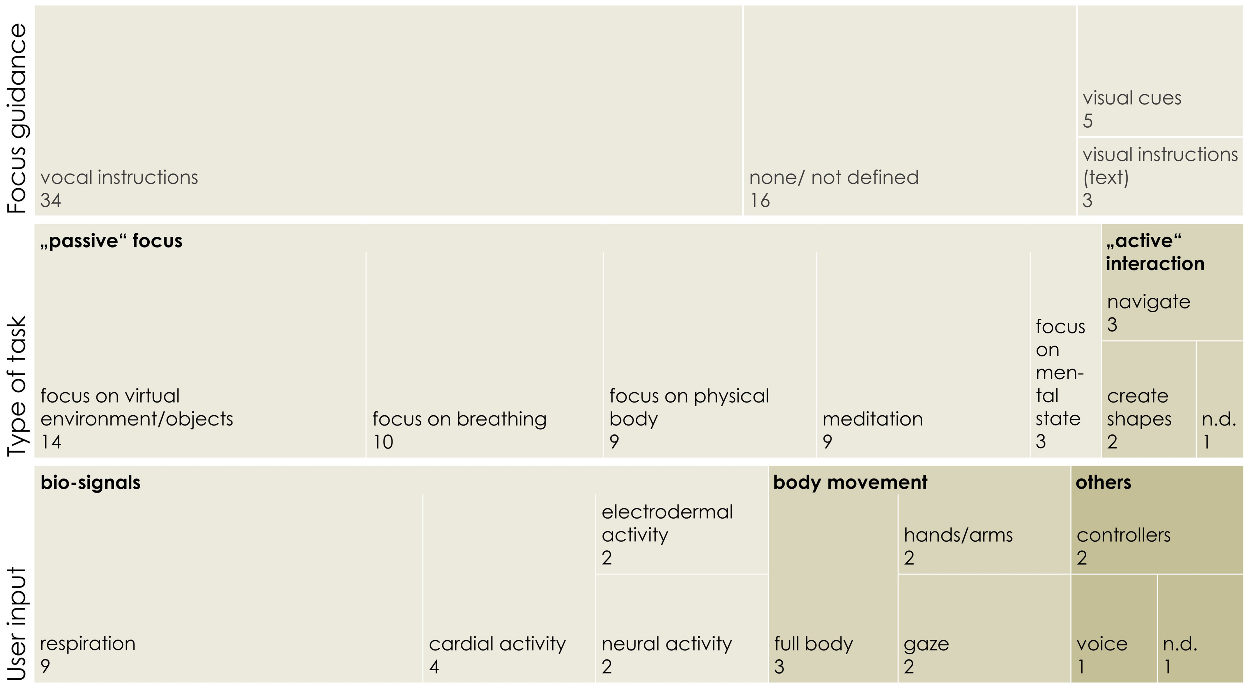


**FIGURE 3 |** Depiction of the different types of focus guidance, task descriptions, and user input. As some papers included different versions or combinations of guidance, tasks and user input, the numbers do not match the total number of papers.

#### 4.3.5. Types of Feedback

More than half of the papers did not include feedback on user interactions or states other than tracking head movements. The systems that did include feedback (**Figure 4**) mostly used visual cues to provide it (e09, e13, e20–e22, e26, e27, e32; d02, d04, d08, d10–d17) and provided it either centrally in front of the user (e13, e20, e22, e26–e28; d04, d08, d09, d11, d16) or both centrally and peripherally (e21, e22, e32; d02, d04, d13–d15, d17). Only three papers presented visual feedback only peripherally (d10, d12, e09). Some of the papers additionally included haptic (e22, e28, d09) or aural feedback (e09, e13, e21; d10, d13, d14). The feedback was mostly provided via the virtual environment (e09, e21, e22, e26, e27, e32; d02, d04, d10–d17) or on virtual objects (e10, e13, e22, e28; d09, d16). Only a few papers included feedback that was presented on a virtual self (e20; d08) or other representations (e27). Most of the feedback was rated as non-quantified (e20–e22, e26, e28, e32; d02, d04, d08–d10, d13–d17).

In conclusion, XR-based mindfulness support in current literature mainly includes visual and aural input, with mostly based on vocal guided meditation which leads the focus to visually presented cues, to one's own breath or bodily sensations. Consequently, most of them either do not require active user input or rely on tracking bio signals which are fed back to the users, mostly visually, within the virtual environment.

## 4.4. Other Influencing Factors

Next to the XR elements, some of the papers included additional factors that might impact on the relation between XR-based mindfulness support and resulting mindfulness. These included individual user characteristics such as previous meditation experience (e11, e24), the type of meditation task within the virtual environment (e13) or the type of mindfulness measure (e13, e24).

## 4.5. Effect Synthesis

### 4.5.1. Manipulation of Immersion

The following section summarizes the results of the EMPIRIC papers that were included in the result synthesis. Only two of the papers that included a measure of an XR-specific perception calculated a correlative relationship between this measure, sense of presence, and *subjective meditation depth* as part of mindfulness (e25, e29). The meditation depth score used for this purpose (Piron, 2003) captures meditation depth on five dimensions: *hindrances*, *relaxation*, *transpersonal self*, *personal self*, and *transpersonal qualities* and additionally allows the specification of *general meditation depth*. In both papers there was a clear positive correlation between the result of the presence measure (SUS Presence Score, Slater et al., 1994) and the indicated meditation depth. In both papers, higher perceived presence was associated with a higher rating of perceived *transpersonal self* [$r = 0.5$ (e25) $r = 0.76$ (e29)] and *personal self* [$r = 0.47$ (e25), $r = 0.67$ (e29)]. While in the work of e25 presence was also moderately correlated to *hindrances* ($r = 0.52$), this relation was not revealed in the study of e29. Regarding the general meditation depth, a moderately positive correlation with presence was confirmed in both papers, $r = 0.52$ (e25), $r = 0.67$ (e29).

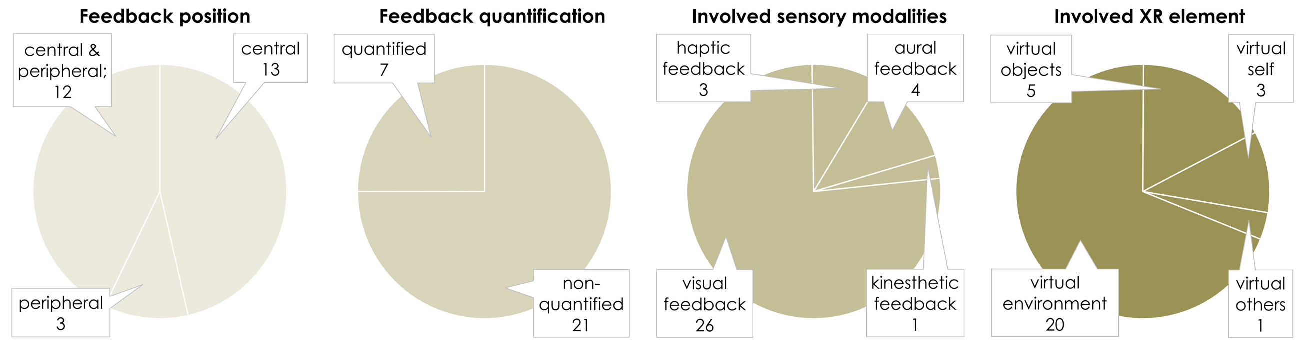


**FIGURE 4 |** Depiction of the different feedback types used in within the literature on XR-based mindfulness support. As not all papers included feedback and some papers included different feedback types, the numbers here do not match the total number of papers.

The results o the effect synthesis are depicted in **Table 2**. While in e10 a significant difference was found between a VR mindfulness intervention and a control group, the comparison between VR mindfulness interactions and non-mediated mindfulness training (e15, e33) led to less explicit results. In e15, a difference between immersive and non-immersive mindfulness was detected, but only on one dimension of the subjective mindfulness measure. In e33 immersive and non-immersive mindfulness training achieved a similar effect on the selected subjective mindfulness item. Compared to less immersive computer screens, as tested in e32 and e19, an immersive system led to higher mindfulness rankings than two-dimensional visual displays. However, e19 revealed sequencing effects demonstrating that the positive performance of the immersive medium occurred only when it was presented first.

The authors of e22 compared an AR and a VR system. Here, no effect of the medium on subjective mindfulness was discovered. However, it is unclear which of the two systems was more immersive, as in the AR condition more interactions with the augmented environment were possible while in the VR condition users meditated in a fully immersive system, but could not interact.

#### 4.5.2. Manipulation of XR Elements

Only one paper recording subjective mindfulness compared different types of environmental representation (e23). In this study, dynamic and non-dynamic environments were compared. The authors did not find a significant impact of environmental dynamics on the perceived mindfulness of the participants (**Table 2**).

Regarding the representation of one's own body in the virtual environment, e20 was included in the results synthesis. Here, the participants perceived a real-time video of their own body from a new perspective and a virtual embodiment illusion was generated via embodiment exercises. However, the authors did not test whether the perceived embodiment toward the presented body had an influence on mindfulness. It was only shown that the virtual embodiment interaction did not have an influence on mindfulness compared to an unmediated meditation. This result was similar to the other two studies comparing an immersive mindfulness interaction with an unmediated one (e15, e33).

The authors of e32 investigated the effect of biofeedback on subjective mindfulness in comparison to a VR mindfulness tool without biofeedback. Here, the above mentioned effect of immersion compared to less-immersive presentation was found, but no difference was detected between a VR condition with and without biofeedback.

## 5. DISCUSSION

The present work aimed to analyze and identify (I) the differences in current research of XR to general HCI in mindfulness research, (II) the design of XR elements, (III) the design of XR-based mindfulness support, and (IV) the impact of XR design on mindfulness in current research. The analysis of along the dimensions of digital mindfulness support proposed by Terzimehić et al. (2019) showed that XR mindfulness research is still very limited compared to the general research on mindfulness in HCI. In particular, the research focuses on the therapeutic effects of VR mindfulness interventions, in which mindfulness serves mainly as a mediator between the virtual interaction and the targeted symptoms. Thus, current XR mindfulness research uses a rather narrowed, instrumental definition compared to the broader possibilities which impact mindfulness as proposed by Terzimehić et al. (2019).

The analysis of virtual environments, virtual objects, virtual self-representation, and virtual others used in current XR mindfulness research revealed, that here too, research has not yet reached the full potential of interactive XR-based mindfulness support. Frequently, immersion is suggested as an influencing factor without addressing its different facets. The most-used virtual environments are nature-inspired scenes or abstract structures, aiming for a sensation of calmness or awe. On the other hand, most of the XR experiences in current research neither include virtual objects, self-representation, or others.

Accordingly, only few papers address the possibilities of XR in more depth and present novel designs or active interactions. The tasks that are included in current literature are mainly based on focusing the virtual environment, or

**TABLE 2 |** Overview of the papers included in the effect synthesis.

| ID | XR conditions | Mindfulness measure | Pre-post | Participants | Results pre-post | Results condition comparison |
|---|---|---|---|---|---|---|
| e15 | (a) VR mindfulness task<br>(b) Non-visualized mindfulness task | Five Facets of Mindfulness Questionnaire (FFMQ, Baer et al., 2008) | Yes | *N* = 33, age: *M* = 44.27, SD = 10.25<br>78.8% female<br>no information on mindfulness practice | (a) Significant increase in three dimensions:<br>describing ($d = 0.85$),<br>awareness ($d = 0.66$),<br>Non-judging ($d = 0.55$) | No significance test to compare conditions<br>(b): less pre-post effects than (a) (dimension: non-judging) |
| e33 | (a) VR mindfulness task<br>(b) non-visualized mindfulness task | One-item scale (non-standardized) | No | *N* = 24, age: *M* = 22.1, SD = 3.3<br>25% female<br>No information on mindfulness practice | — | No significant difference between (a) and (b) |
| e19 | (a) VR mindfulness task<br>(b) Computer screen mindfulness task | Meditative Experiences Questionnaire (MEQ, Frewen et al., 2011) | Yes | *N* = 96, age: 17–22 years<br>65.3% female<br>68.75% low/no mindfulness practice | — | Significant higher ratings in (a) compared to (b)<br>significant sequence effects |
| e22 | (a) VR mindfulness task<br>(b) AR mindfulness task | Toronto Mindfulness Scale (TMS, Lau et al., 2006) | No | *N* = 12, age: *M* = 45, SD = 11<br>100% female<br>58% regular mindfulness practice | — | No significant difference between (a) and (b) |
| e10 | (a) VR mindfulness task<br>(b) Control group (no task) | Experiences of Mindfulness During Meditation scale (EOM-DM, Reavley and Pallant, 2009) | Yes | *N* = 60, age: *M* = 83.03, SD = 7.6<br>69% female<br>no information on meditation experience | Significant increase in mindfulness experience | Significant group-time-interaction (control-group: no increase) |
| e32 | (a) VR mindfulness task<br>(b) Computer screen mindfulness task<br>(c) VR mindfulness task with biofeedback | MEditation DEpth Questionnaire (MEDEQ, Piron, 2003) | No | *N* = 43, age: *M* = 28.7<br>60.4% female<br>low/no mindfulness practice | — | Significant higher ratings in (a)/(c) compared to (b)<br>no significant difference between (a) and (c) |
| e20 | (a) VR embodied body swap<br>(b) Non-visualized imaging | State Mindfulness Scale (SMS, Tanay and Bernstein, 2013) | Yes | *N* = 16, age: *M* = 30.56, SD = 10.86<br>75% female<br>no regular mindfulness practice | Significant increase in both dimensions:<br>mental events ($d = 2.73$)<br>bodily sensations ($d = 2.04$) | No significant difference between (a) and (b) |
| e23 | (a) Dynamic virtual environment<br>(b) Static virtual environment | Toronto Mindfulness Scale (TMS, Lau et al., 2006) | No | *N* = 15, age: *M* = 38.4, SD = 16.7<br>46.7% female<br>40% regular mindfulness practice | — | No significant difference between (a) and (b) |

the current state. The number of papers that include active, body-based interactions that might help focusing on the physical body is limited. Nonetheless, many papers in current literature at least focus on giving feedback on the user's bodily states. Biofeedback can be presented and perceived via various digital media. On the contrary, the XR element of self-representation and the XR-specific perception of virtual embodiment are unique to XR and raise new possibilities to support mindfulness via body-based feedback. However, embodying avatars as digital self-representation was only used in one paper.

The results synthesis reveals that a large proportion of current research has not tested the relationship between different XR elements and (subjective) mindfulness. However, initial results show that immersion *per se* within a non-interactive virtual natural environment only leads to a limited enhancement of mindfulness compared to conventional guided meditation tasks. However, due to the lack of research on more interactive systems, these results may only apply for XR systems with low interactivity and do not imply a low potential of XR-based mindfulness support *per se*.

## 5.1. XR-Based Mindfulness Support—Opportunity to Provide Presence-In?

### 5.1.1. Exploring Virtual Environments

As stated in the results, a large part of the papers mainly focuses on the recreation and presentation of natural scenes. Experiences in nature are closely linked to mindfulness (Zhu et al., 2017; Van Gordon et al., 2018). Thus, walking in a forest can be seen as a mindfulness inducing activity, providing natural *presence-in* (Zhu et al., 2017). However, it has not yet been researched whether an interaction with a virtual nature-themed environment has a similar effect on mindfulness as a real experience within nature. Some of the papers focused instead on more abstract environmental design, as abstract designs should increase curiosity toward the environment and give the opportunity to explore unknown shapes and terrains (Tinga et al., 2019) without judgment. Again, however, according to the current state of research, it remains open as to whether the postulated advantages of abstract virtual environments affect the state of mindfulness. Overall, hardly any studies have been conducted so far that researched the impact of different virtual environments on mindfulness. In comparison to real environments, XR enables to manipulate the environmental representation and behavior systematically. However, this potential has not been fully tapped so far.

#### 5.1.2. From Guided Meditation to Interactive Mindfulness Interactions

As pointed out in section 4.3, there are only a few studies in which users actually interact with the virtual system, while the predominantly used tasks defined by vocally guided meditation within a calming environment. These results are in contrast to the work of Salehzadeh Niksirat et al. (2017), Niksirat et al. (2019), and Terzimehić et al. (2019) who emphasize the importance of interactivity and appropriate feedback within a digitally supported mindfulness practice. Both research groups address *slow design* (Grosse-Hering et al., 2013) as a design guideline for interactive mindfulness tasks. To actually evoke this interactive mindfulness, we propose that XR-based mindfulness support should consider kinetic interactions. Accordingly, the results of user interviews in Zaharuddin et al. (2019) emphasize the importance of interactions when creating mindful XR solutions. A first step in this direction are the systems of Potts et al. (2019) or Roo et al. (2017), that include active body movement. It would be interesting to examine to what extent the guidelines from research on slow design are applicable to XR and thus how active, kinetic XR interactions must be designed in order to support mindfulness.

#### 5.1.3. Ambient Environmental Feedback

Besides the immersion in a mindfulness-inducing environment and the interaction with it, the presentation of biofeedback within the ambient environment is a great opportunity to provoke presence-in. Depending on its presentation biofeedback in XR serves less as a quantification of current state and more as a way to project the state of mind and make it perceptible in new, innovative ways. Similarly to general environmental representation, there are two branches of development here - embedding biofeedback in a naturalistic environment, and more abstract forms of representation. Future work here, similar to the general work on environmental representation, should address what kind of representation of virtual biofeedback has mindfulness-inducing effects.

### 5.2. Embodied VR—Opportunity to Provide Embodied Mindfulness?

Following on from immersive experiences, we proposed virtual self-representations and embodiment illusions as an opportunity to create embodied mindfulness experiences. While mindfulness is based on body perceptions (Heeter, 2016; Khoury et al., 2017; Niksirat et al., 2019), a regular mindfulness practice can increase interoceptive body awareness (Sze et al., 2010; Kühle, 2017) leading to an increased clarity, accuracy and immediacy in the perception and detection of body perceptions. The link between these two constructs is not yet reflected in the work on XR-based mindfulness support. Only one of the studies presented here included (subjective) body awareness as a dependent variable (Costa et al., 2019). The investigation of body sensations in XR within other research fields explores various interactions with one's virtual body, combining different visual, vestibular, and haptic stimuli to produce stimulation via sensory alignment or misalignment (Filippetti and Tsakiris, 2017; Czub and Kowal, 2019; Monti et al., 2020). In contrast, only one of the papers presented in our review used virtual embodiment illusions in XR and investigate their effects on mindfulness (Cebolla et al., 2019). Although some of the papers highlighted the importance of including the user's body (Roo et al., 2017), many researchers have not yet drawn the conclusions and implemented a virtual self-representation. Future work should address whether a virtual self-representation can promote mindfulness in XR. It should further investigate the type of self-representation, whether a realistic avatar is mandatory or whether a modified, enhanced or individualized virtual self-representation has a positive influence on XR-based mindfulness support. Similarly to the interactivity of the objects in an XR-based mindfulness support, it should be researched which kind of interaction with the own virtual body can be useful.

#### 5.2.1. XR-Specific Perceptions and Mindfulness

In addition to the direct influences of the different XR elements on mindfulness, it is worth mentioning that only a few of the presented studies examined to what extent the proposed XR-based mindfulness support affected the XR-specific perception itself. XR research usually investigates whether the experience in a virtual environment is accompanied by a sense of presence, whether the embodiment of an avatar leads to a sense of embodiment, or whether the presentation of virtual others leads to a sense of social presence. Thus, they can be seen as a kind of indicator as to whether the content of a virtual experience had these desired effects. An interesting research question would therefore be not only whether different XR conditions had an influence on mindfulness, but also whether and to what extent mindfulness is related to common XR-based phenomena.

### 5.3. Framework for XR-Based Mindfulness Support

Based on our literature analysis and the existing frameworks and guidelines on digital mindfulness support (Salehzadeh Niksirat et al., 2017; Zhu et al., 2017; Niksirat et al., 2019), XR-based mindfulness support (Roo et al., 2017), and XR intervention evaluation (Wienrich et al., 2020), we propose a framework for

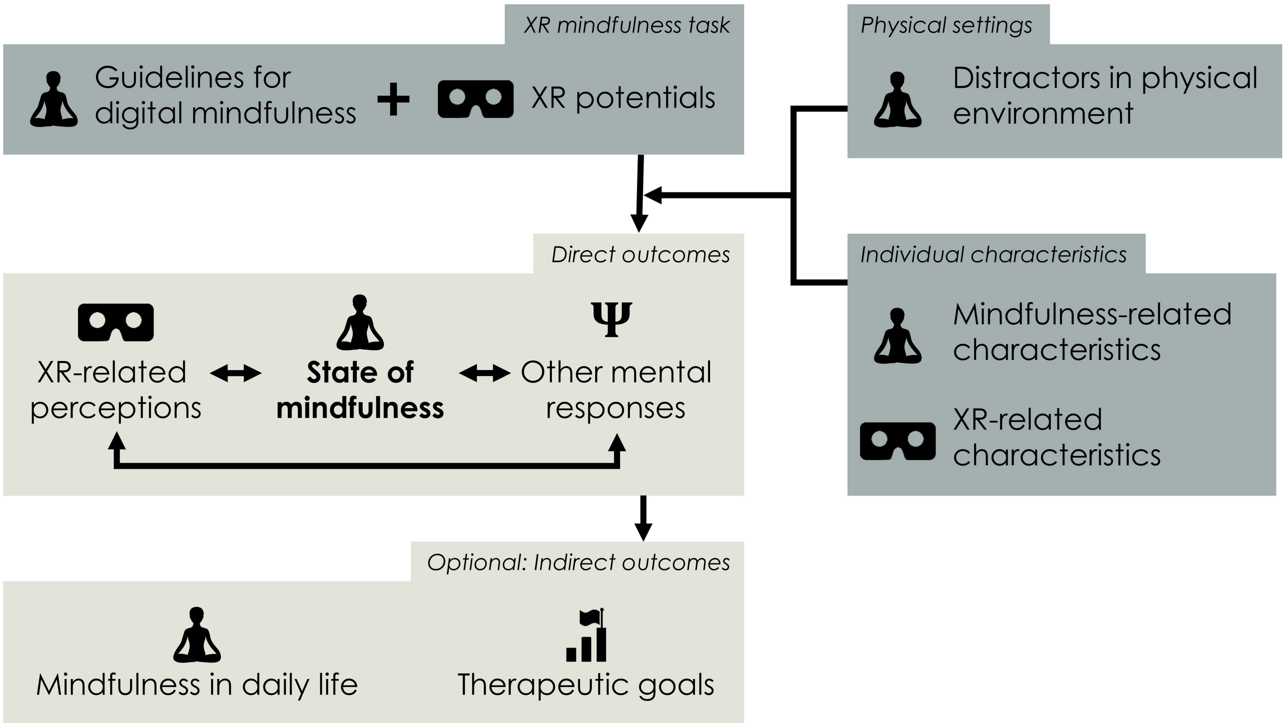


**FIGURE 5 |** Framework of the influence of XR elements on mindfulness and mindfulness-related concepts. The darker boxes include variables that impact or moderate the outcomes of our interactions. The lighter boxes represent the outcomes, divided into direct responses to the XR experience and indirect target outcomes.

design and evaluation of XR-based mindfulness support. Using the modifiable XR elements and the guidelines for mindful interaction, we can create interactions that take into account the constraints and possibilities of XR, and meet the requirements for mindful interactions. The result is shown in **Figure 5**.

### 5.3.1. Design of a XR-Based Mindfulness Task

The first level of the framework, *XR mindfulness task*, summarizes a set of *guidelines for digital mindfulness support*. We distinguish between guidelines for general design, focus guidance, feedback, and user input. The resulting guidelines are depicted in **Table 3**. While some of the guidelines focus on designing the XR elements in a specific manner, e.g., minimalistic instead of complex, others focus on the inclusion of different elements, e.g., focus-enabling as well as challenging elements, multiple sensory cues, or body- and mind-based interactions.

These guidelines can be applied to the four XR elements (Wienrich et al., 2020): (a) virtual environment, (b) virtual or augmented objects, (c) virtual body and self-representation, and (d) virtual others. The combination of those XR elements and the guidelines for digital mindfulness support leads to a number of possible research questions which can help approaching future research systematically and defining design guidelines for each of the XR elements. **Figure 6** gives a short overview of the design space and exemplary research questions within each of the elements and guideline categories. Since the empirical results so far are not sufficient to create a complete set of design guidelines, the overview is limited to some sample questions.

Not every XR-based mindfulness support needs to include all of the XR elements. Nevertheless, the overview offers the possibility to choose the XR element best suited to the respective task or goal. Thus, the different elements are helpful in implementing the guidelines for mindful interaction in different ways: environmental representation is well-suited to showing peripheral biofeedback, without being instrumentalized. Virtual objects may be more likely to assist in facilitating body sensations via soft haptic feedback. While an interactive virtual self-representation might help understanding bodily consequences, virtual others might be included to enable focus by leading as an example.

### 5.3.2. Mindfulness as Target Outcome: Related Concepts

To examine the effects of an XR-based mindfulness support, it is necessary to consider the second stage of the framework, *direct outcomes*, that might be related to the *state of mindfulness*. Although mindfulness was not the main goal in some of the literature, we still claim the importance of examining the influence of an XR-based mindfulness support on state mindfulness. Therefore, the *state of mindfulness* forms the center of our framework. As proposed in Terzimehić et al. (2019) state mindfulness can be measured in various ways,

**TABLE 3** | Guidelines for mindfulness task design (derived from: (Zhu et al., 2017; Salehzadeh Niksirat et al., 2017; Roo et al., 2017; Niksirat et al., 2019).

| | Guidelines: choose |
|---|---|
| General design | Minimalism instead of complexity |
| | Multimodality instead of unimodality |
| | Enabling and/or challenging elements |
| Guidance | Subtle instead of direct guidance |
| | Peripheral instead of central guidance |
| | Sensory cues instead of vocal guidance |
| Feedback | Soft instead of direct feedback |
| | Non-quantified instead of quantified feedback |
| | Peripheral instead of central feedback |
| | Predictable and non-predictable elements (acceptance) |
| Interaction | Active and passive interaction |
| | Body-based and mind-based interaction |
| | Explorative instead of instrumentalized interaction |
| | Slow and repetitive interactions |

for example via physiological measures (Bostanov et al., 2018), subjective scales (Bergomi et al., 2013), or movement detection (Salehzadeh Niksirat et al., 2017).

To analyze the mechanisms of XR-based mindfulness support, we further list *XR-specific perceptions* and their relation to mindfulness, which can be measured via subjective scales: sense of presence(e.g., IPQ, Schubert et al., 2001), sense of embodiment (e.g., VEQ, Roth and Latoschik, 2020), sense of social presence (e.g., SPGQ, De Kort et al., 2007), and simulation sickness (e.g., SSQ, Kennedy et al., 1993). In addition, *other mental responses* that are generally associated with mindfulness and their relationship to XR-specific perceptions can be considered. In contrast to the XR-specific perceptions, there is data from psychological research that deals with how mindfulness is related e.g., to emotion regulation (Feldman et al., 2007), cognition (Zeidan et al., 2010), or stress (Kabat-Zinn, 2003). The second level of the framework thus arises a second set of possible research questions addressing the current research gap concerning the relation of mindfulness to XR-specific perceptions and other mental responses.

#### 5.3.3. Mindfulness as Mediator: Indirect Outcomes

In most of the EMPIRIC studies, mindfulness was used as a mediator for other, mostly therapeutic goals. Some other studies not only considered state mindfulness, but examined whether XR-based mindfulness support can have a longer-term impact on mindfulness in daily life. Therefore, we add a third level to the framework, *indirect outcomes*. Since some of the studies only examined the impact of the XR interaction on these targets, we want to highlight here that for a full understanding of the mechanisms of an XR-based mindfulness support it is important to also consider the role of state mindfulness and other, XR-based mindfulness support, as mediators of these outcomes.

#### 5.3.4. Moderating Effects of Physical Surroundings and Individual Characteristics

Another point is the moderating influence of *individual characteristics*, as highlighted by Wienrich et al. (2020). The former addresses the ability to distinguish reality and virtuality or the tendency to perceive simulation sickness. The latter includes for example trait mindfulness or experience with mindfulness practices. The physical setting of an XR interaction can affect the choice of the appropriate medium and its effects on mindfulness. While in a noisy or busy environment VR helps with masking, in a quiet setting AR-systems might be more appropriate to create mindful exploration.

### 5.4. Limitations

While our paper provides new insights into current research and research gaps on XR-based mindfulness support, the results are limited in a few ways. First, it can be argued that the strong therapeutic focus of the EMPIRIC papers underlies the selected database. Of course, PubMed certainly provides some therapeutic bias. However, we conducted a scanning procedure across several other psychological databases which did not reveal any additional papers to our initial search.

As described in section 3, we did not analyze the impact of the design of XR-based mindfulness support on usability, user experience or user acceptance which were addressed in some of the DESIGN as well as some EMPIRIC papers. The focus of this work was to describe the XR elements in current mindfulness tasks and their impact on mindfulness and mindfulness-related outcomes. Nevertheless, an analysis of these more practical topics could give broader insights into the design possibilities of XR-based mindfulness support and should be included in future analyses. Additionally, we limited our effect analysis to papers that included subjective measures of mindfulness and did not extend it to papers with physiological measures, as we wanted to make sure that the effects were actually related to mindfulness. Commonly recorded physiological measures such as skin conductance and heart rate are not specific to mindfulness or the valence of the psychological state but might be more indicative of the level of arousal, or a calming or relaxing effect (Costa et al., 2019; Tinga et al., 2019) of the interaction. Future work should nevertheless address whether and how XR-based mindfulness support has an influence on physiological mindfulness measures and how these can be distinguished from general influences of XR on physiological measures (e.g., distortion of EEG data, Hertweck et al., 2019).

In section 2.2.3, we emphasized that the concept of (embodied) mindfulness is closely related to that of body awareness. The current review did not yet include body awareness *per se*, as the focus was on initially analyzing current XR-based mindfulness support. Future work could address the extent to which XR-based mindfulness support is related to body awareness, or on the other hand the extent to which XR body awareness tasks are associated with a change in mindfulness.

| | **General Design**<br>• Minimalism<br>• Multimodality<br>• Enabling and/or challenging elements | **Guidance**<br>• Subtle guidance<br>• Peripheral guidance<br>• Sensory cues | **Feedback**<br>• Soft<br>• Non-quantified<br>• Peripheral<br>• Partly unpredictable | **User Input**<br>• Active and passive<br>• Body-based and mind-based<br>• Exploratory<br>• Slow and repetitive |
|---|---|---|---|---|
| **Virtual Environment**<br>• Sensory representation<br>• Behavioral representation | Which kind of **virtual background** facilitates/challenges mindfulness? | Which kind of **environment-based guidance** facilitates/challenges mindfulness? | Which kind of **environment-based feedback** facilitates/challenges mindfulness? | Which input modality fits mindful interactions with the **virtual environment**? |
| **Virtual Objects**<br>• Sensory representation<br>• Behavioral representation | Which kind of **virtual objects** facilitate/challenge mindfulness? | Which kind of **object-based guidance** facilitates mindfulness? | Which kind of **object-based feedback** facilitates mindfulness? | Which input modality fits mindful interactions with **virtual objects**? |
| **Virtual Self**<br>• Sensory representation<br>• Behavioral representation | Which kind of **self-representation** facilitates/challenges mindfulness? | Which kind of (virtual) **self-based guidance** facilitates mindfulness? | Which kind of **self-based feedback** facilitates mindfulness? | Which input modality fits mindful interactions with a **virtual self**? |
| **Virtual Others**<br>• Sensory representation<br>• Behavioral representation | Which kind of **virtual others** facilitate/challenge mindfulness? | Which kind of (virtual) **other-based guidance** facilitates mindfulness? | Which kind of **other-based feedback** facilitates mindfulness? | Which input modality fits mindful interactions with **virtual others**? |

**FIGURE 6 |** Overview of the combinations of design guidelines for digital mindfulness support and the XR elements.

### 5.5. Conclusion

Mindfulness is a topic that has received increasing attention in HCI over the last decade. In the field of XR, several researchers have discussed the potential of XR-based interactions support. The present paper provides a systematic analysis of the current literature with regard to the influence of different XR contents on mindfulness. The results of our review show that XR mindfulness research has so far focused on mindfulness in a rather limited way. The analyzed papers had mainly therapeutic orientation and treated mindfulness as a mediator for other mental and physical perceptions. Additionally, we revealed that so far a rather limited fraction of XR elements have actually been researched for their influence on mindfulness. Current empirical work predominantly uses vocally guided meditation, in which neither the user's body nor interactivity with the XR system are involved. The analysis of the results indicated that currently examined XR-based mindfulness support systems hardly have a positive influence on mindfulness compared to conventional meditation. However, recent developments in technology and design show potential for more powerful XR-based mindfulness support. Our framework is a structured approach to define the design space for XR-based mindfulness support. It combines design guidelines for digital mindfulness support with the elements and mechanisms of XR interventions leading to a variety of research questions and the possibility to create new, XR-specific design guidelines for mindful interactions. As a result, it enables to systematically close research gaps and get a comprehensive picture of XR-based mindfulness support.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

## AUTHOR CONTRIBUTIONS

ND and CW contributed to the conception of the literature analysis and the manuscript and wrote sections of the manuscript. ND organized and performed the analysis. MEL supervised the structuring of results. MEL and CW supervised the paper writing process.

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frvir.2021.644683/full#supplementary-material

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# A. APPENDIX

**TABLE A1 |** Tasks, user input, and feedback presented in the papers with interactive mindfulness tasks.

| ID | Task | User input | Feedback |
|---|---|---|---|
| d02 | Navigate through environment | Controllers | Virtual locomotion |
| d03 | Navigate through environment | Bio data: not defined<br>Motion: full body | Virtual locomotion |
| d04 | Focus on virtual objects and navigate through environment | Motion: gaze | Virtual locomotion |
| d08 | Focus on breathing and keep posture | Bio data: respiration | Expansion and contraction of tree trunk; expansion of colors; and blooming with changing breath rhythm |
| d09 | Focus on virtual objects | Bio data: cardial activity | Pulses synchronized with heart beat |
| d10 | Shape environment | Bio data: neural activity<br>Motion: full body | Blooming flowers and ambient sounds |
| d11 | Focus on breathing | Bio data: respiration | Sparkling dots in a tree |
| d12 | Focus on breathing and physical body | Bio data: respiration and neural activity | Opening flowers |
| d13 | Meditation | Bio data: neural activity and electrodermal activity | Changing movement patterns |
| d14 | Focus on virtual environment | Bio data: respiration | Control of position above ocean, movement of clouds |
| d15 | Focus on mental state | Bio data: neural activity and cardial activity<br>Motion: hands/arms | Change in colors and shapes of the environment |
| d16 | Not defined | Motion: gaze | Triggering events by focusing objects |
| d17/e32 | Focus on physical body and virtual objects | Bio data: neural activity | "Energy bubble" surrounding the user becomes more visible; platform movement signalling concentration |
| e08 | Focus on breathing and virtual objects | Voice | Virtual locomotion |
| e09 | Focus on virtual environment | Bio data: electrodermal activity | Increased/reduced intensity of fog |
| e10 | Focus on virtual objects | Controllers | Object movement |
| e13 | Focus on breathing and physical body | Bio data: respiration | Adjustment of audio prompts, outward-moving, growing blue particles |
| e20 | Focus on physical body | Motion: full body | Mirroring of body movements |
| e21 | Focus on virtual environment | Bio data: respiration | Control of position above ocean movement of clouds |
| e22 | Shape environment; focus on virtual environment; | Bio data: respiration and cardial activity | Changed topology; moving sea, changing weather and landscape |
| e26 | Focus on breathing | Bio data: respiration | Growing/shrinkage of a white cloud |
| e27 | Meditation (empathy) | Bio data: respiration and neural activity | Illumination of panels on the virtual floor; growing/shrinkage of shining circles around statues |
| e28 | Focus on virtual objects | Bio data: cardial activity | Pulses synchronized with heart beat |