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Nature-based mindfulness-compassion programs using virtual reality for older adults: A narrative literature review

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The global population is aging at an unprecedented rate, increasing the necessity for effective interventions targeting the mental health needs of older adults. Technology addressing the aging process of older adults (i.e., gerontechnology) is an avenue for the efficient delivery of programs that enhance adult well-being. Virtual reality (VR) is a type of gerontechnology with the potential to improve mental health and well-being (e.g., by increasing resilience, mindfulness, compassion, connection with nature, and decreasing stress, depression, anxiety); however, evidence in this area is currently lacking and more rigorous research on the acceptability, feasibility, and effectiveness of mental health programming *via* VR for older adults, such as nature, mindfulness, or compassion-based interventions, is necessary. The present literature review: *1)* explores, synthesizes, and critically evaluates the literature on older adult mental health, well-being and gerontechnology, with a focus on virtual reality-based nature, mindfulness, and compassion-based interventions; *2)* examines research to date on the relationship between virtual reality technology and nature, mindfulness, and self-compassion; *3)* identifies gaps, contradictions, and limitations of existing research; *4)* identifies areas for further investigation; and *5)* discusses implications for research and clinical practice.

KEYWORDS

compassion, mindfulness, nature, virtual reality, gerontechnology, well-being, mental health, older adults

Introduction

Global population aging has been accelerating exponentially over the recent decades with the proportion of older adults predicted to surpass that of children for the first time in world history (United Nations Department of Economic and Social Affairs, 2013; World Health Organization, 2021). Critically, a substantial portion suffer from both diagnosed and sub-clinical mental health conditions (Ciechanowski et al., 2004; Gum et al., 2009; Institute of Medicine, 2012; Karel et al., 2012). Despite their need, older adults access mental health services less frequently than younger populations (Klap et al., 2003; Wang et al., 2005; Karlin et al., 2008; Bogner et al., 2009; Mental Health Foundation, 2018). New strategies to successfully target older adults' mental health and well-being needs are therefore urgently required. Novel methods to improve the quality of life of older adults, benefitting from recent technological developments, have been applied in various settings to deliver distance interventions, encourage healthier lifestyles, and conduct non-invasive assessments (Preschl et al., 2011; Kim et al., 2017; Brimelow et al., 2020). Technology developed to meet older adults' needs, or Gerontechnology (Bouma et al., 2009) has been increasingly integrated into daily life routines (Wootton, 2012; Calvo & Peters, 2013; Lattanzio et al., 2014; Bercovitz & Pagnini, 2016) and may have the potential to ameliorate treatment accessibility and quality (Kvedar et al., 2014). However, to maximize the effectiveness of these technology-based modalities, it is necessary to move beyond conventional telehealth methodologies and investigate fresh modalities of mental health provision for older adults, such as Virtual Reality (VR). VR may be particularly effective for older adults when incorporating natural settings, and elements of interventions focused on augmenting mindfulness and compassion. Thus, the aims of the present literature review are to: *1*) explore, synthesize, and critically evaluate the literature on older adult mental health, well-being and gerontechnology, with a focus on virtual reality-based nature, mindfulness, and compassion-based interventions; *2*) examine research to date on the relationship between virtual reality technology and nature, mindfulness, and self-compassion; *3*) identify gaps, contradictions, and limitations of existing research; *4*) identify areas for further investigation; and *5*) discuss implications for research and clinical practice.

Trends in older adult mental health and well-being

Global population trends predict a dramatic increase in the proportion of the population considered to be older adults (i.e., persons aged 60 years and older) and a general acceleration in population aging worldwide (UN DESA, 2013; WHO, 2021). Population aging can be defined as an increasing population share of older individuals, where decreases in mortality lead to decreases in fertility (UN DESA, 2013). The global share of older adults is expected to increase by more than twofold, from 841 million people in 2013 to over 2 billion in 2050, which will be approximately 21.1% of the worldwide population (UN DESA, 2013). With the current number of older adults at slightly over 1 billion, the shift in the global population's age distribution is already being experienced (WHO, 2021). By 2047, it is predicted that the number of older adults will exceed the number of children for the first time in the history of the world (UN DESA, 2013). Additionally, the fastest growing portion of the population is the "oldest-old," typically qualified as persons aged 85 and over. This segment of the population also has the highest healthcare needs and costs, due to medical comorbidities (UN DESA, 2019).

The process of aging consists of much diversity, defined by large inter-individual heterogeneity in general functioning, physical and mental health, coping skills, and access to socio-economic resources (Karel et al., 2012). Notably, a significant proportion of older adults suffer from mental health and cognitive conditions (Gum et al., 2009; IOM, 2012; Karel et al., 2012). For example, Karel and others (2012) found that of adults 65 years of age and older, approximately 20.4% met diagnostic criteria for a mental disorder over a period of 12 months. Additionally, mood disorders, such as depression, are becoming a growing concern for health services given their current prevalence in older adults, as well as the predicted trajectory of depression to be the main cause of disease burden by 2030 in higher income countries (Rodda et al., 2011). Of further concern, rates of depression are slightly more prevalent in the oldest old, who as mentioned previously, are the fastest growing proportion of the older adult population (Byers et al., 2010; UN DESA, 2019). These rates do not account for the significant number of older adults who experience clinically significant distress while not officially meeting the criteria for a psychiatric diagnosis or receiving a formal diagnosis (Ciechanowski et al., 2004), indicating that population rates of mental health challenges in older adults are likely underreported and that the magnitude of psychiatric difficulties could be vaster than realized. Furthermore, older adults with psychiatric symptoms are more likely to experience comorbid cognitive challenges (Gum et al., 2009), as well as poorer physical health outcomes with higher rates of hospitalization and emergency room visits (Bartels et al., 2003; IOM, 2012).

However, evidence indicates that older adults are less likely to access mental health services (Klap et al., 2003; Wang et al., 2005; Karlin et al., 2008; Bogner et al., 2009; MHF, 2018). Additionally, they are less likely to receive mental health care from specialists, compared to younger and middle-aged adults (Klap et al., 2003; Bogner et al., 2009). Common barriers to older adult mental health service provision cited in the literature include stigma, lack of information, perceived costs, mobility restraints, lack of specialized health professionals, limited mental health literacy, and beliefs that symptoms of mental health illnesses are a normal part of the aging process (Farrer et al., 2008; Bogner et al., 2009; Karel et al., 2012; Drozd et al., 2016; Titov et al., 2016; Morgan et al., 2017; Rost et al., 2017).

Given that mental health problems and cognitive impairments, such as dementia, are often under-discovered and undertreated in general medical practitioner settings (Ganguli et al., 2004; Wang et al., 2005; Unützer et al., 2006), the high rates of cognitive and psychological challenges amongst older adults (e.g., Gum et al., 2009; IOM, 2012; Karel et al., 2012), and the unprecedented aging of the population (e.g., GC, 2014; UN, 2013; WHO, 2017), there is a need for a paradigm shift encompassing innovative solutions to the approach and delivery of geriatric mental health care. Therefore, a holistic, collaborative, culturally-informed approach to care that focuses on the overall health and well-being of older adults appears to be essential to achieve positive quality of life outcomes (Karel et al., 2012; Bartels & Naslund, 2013; Pywell et al., 2020).

An approach that not only aims for normal aging, but instead "successful aging" thus seems necessary to achieve this goal (Rowe & Kahn, 1987; *see* also Rowe & Kahn, 1997; Rowe & Kahn, 1998). Building on the MacArthur model of successful aging (Rowe & Kahn, 1987), Rowe and Kahn's (1997) scientific review and conceptualization of aging describes successful aging as comprising three key factors: *1*) low likelihood of disease or disability related to disease, *2*) strong capacity for cognitive and physical functioning, and *3*) active involvement and interest in life. Rowe and Kahn (1997) postulate that while these factors on their own are important, it is their synergistic quality when combined that leads to successful aging. Therefore, it is theorized that approaches to care for older adult aging that emphasize these components are more likely to be effective at enabling positive aging experiences (Rowe & Kahn, 1997). During the past decades, this theory has been backed by an increased scientific attention to the psychological empowerment of older adults and has received continued interest in gerontological research, theory and practice (e.g., Hank, 2011; Pruchno & Carr, 2017). However, it has not been without controversy and critique, leading to an updated and revised version of the MacArthur model of successful aging (Rowe & Kahn, 2015). Main critiques of the original MacArthur model include, but are not limited to, a need for increased attention to the subjective aspects of successful aging, loosening of and expanding the successful aging criteria, defining successful aging in a way that is more inclusive and avoids discrimination or stigmatization of those who are not aging well, and Western cultural bias (Martinson & Berridge, 2015).

Gerontechnology

Conceptualizations

The term "Gerontechnology" was first coined by Graafmans and Brouwers (1989) and refers to the mixing of the scientific fields of gerontology and technological engineering. The word itself is a blend of "gerontology" (i.e., the study of aging) and "technology" (i.e., the creation and supply of technological products, services, and environments) (Fozard et al., 2000). It can be defined as the development and use of technology for the benefit of aging and older adults (Fozard et al., 2000). In Bouma and others' (2009) review, gerontechnology is described as an essential determinant to the healthy aging and quality of life of older adults. Bouma et al. (2009) discusses how the field of gerontology often overlooks: *1*) the environment of aging people, *2*) proactive prevention-based solutions, instead seeking out disease countering strategies, and *3*) active participation of older adults as their own agents of change in the healthy aging process. The impact and ability of technology to change the environment in which people age is highlighted as a key utility of using gerontechnology as a prevention-based intervention to promote holistic, healthy aging (Bouma et al., 2009). Fozard et al. (2000)'s seminal review highlights six key areas where gerontechnology has the potential to improve the aging process of older adults: *1*) housing; *2*) communication; *3*) personal mobility and transportation; *4*) health; *5*); work; and *6*) recreation and self-fulfillment. Of particular relevance, gerontechnology is posited to help with the healthy aging of older adults, for instance by preventing or postponing health problems through nonmedical interventions that help to counteract deterioration in psychological and physiological functioning, which is often linked to aging (Fozard et al., 2000). Additionally, Fozard and others (2000) points to the potential utility of computer games and visual arts-based computer programs as an under-tapped resource for self-fulfillment and well-being in older adults.

However, in order for gerontechnology to be successfully implemented, it needs to be perceived as acceptable by its primary target, namely, older adults. According to Davis's (1989) technology acceptance model (TAM), two primary components effect an individual's acceptance of technology: *1*) perceived usefulness of the technology, and *2*) perceived ease of use. That is, potential use of technology is often predicted by the extent that individuals believe it will be helpful to them. However, even if potential technology users think that a specific technology is useful, they may also think that it is too challenging to use, and that the effort involved in using the technology outweighs its benefits (Davis, 1989). Therefore, based on the TAM, effective gerontechnology should be clearly beneficial to its users, while also being developed and presented in a way that is easy for users to engage with. This hypothesis has been empirically supported through a meta-analysis conducted by Zhou and others (2020), where it was found that perceived usefulness and perceived ease of use had significant positive impacts on older adults' attitudes and behavioral intentions related to gerontechnology.

Current applications

The global impact of the aging society is further compounded by another major societal change: the technological revolution. In particular, these transformations raise questions for researchers, policymakers, and practitioners as to whether computer-based technologies will further widen the divide of age segregation, amplifying the isolation of older people, or instead break down generational barriers (Rowe & Kahn, 2015). Despite common perceptions, a growing body of research is beginning to highlight the potential acceptability of technology for older adults as evidenced by its increased integration into their daily life routines (Wootton, 2012; Calvo & Peters, 2013; Lattanzio et al., 2014; Bercovitz & Pagnini, 2016). For instance, in higher income countries, adults over 65 years of age appear to be increasingly Internet and tech-savvy (Wagner & Wagner, 2003; Crabb et al., 2012; Reardon 2012; Cangelosi and Sorrel, 2014). Estimates of older adults in the USA indicate that over 50% use email or the Internet, with around 70% of this population using them every day (Reardon, 2012). Additionally, approximately 11% of older adults own a smartphone (Reardon, 2012).

While the Internet, email, and text messaging are, at this time, the most widespread and accessible types of computer-based technology for older adults, more advanced forms of technology (e.g., patient portals, smartphone applications) that help older adults manage acute and chronic health-based conditions also appear to be acceptable, based on findings from recent scientific studies (for e.g., *see* Chang & Im, 2014; McMahon et al., 2014; Taha et al., 2014; Wong et al., 2014). Gerontechology is currently applied in a wide range of health-based domains such as physical activity and mobility, home care experience, and overall wellness. For example, technology has been used to assist with medication adherence in home care settings (Lapane et al., 2012; Reeder et al., 2013). Pedometer-based technology used to help with flexibility and frequency of exercise has been implemented in older adult populations through DVD-based exercise programs, tablet computers, and software applications (Bickmore et al., 2013; McAuley et al., 2013; Silveira et al., 2013). Information technology has been used to augment knowledge of and adherence to practices that improve general wellness (Cocosila et al., 2009; Thompson et al., 2011; Xie, 2011); for instance, focusing on improving mental health by reducing isolation and loneliness (McCausland & Falk, 2012). Furthermore, VR headsets have become more accessible and immersive for older adults with tools such as head-mounted display (HMD) and the cave automatic virtual environment (CAVE) that facilitate increased interaction with virtual environments, thereby improving engagement and motivation to use technological interventions (Tuena et al., 2020). The development of mobile application technology with visors and/or tracking systems (e.g., Google Cardboard) allows for further options that are accessible and provide relatively immersive virtual environments (Fang et al., 2017; Tuena et al., 2020). These VR technologies allow for the development of tailored exercises that can be meaningfully manipulated and controlled to virtual environments, enabling effective rehabilitation interventions (Winstein et al., 2016). However, the current gerontechnology research-base is heavily weighted towards biomedical and physical health interventions, often overlooking the potential for gerontechnology as a psychological intervention (Vailati-Riboni et al., 2020a). Kwon (2016)'s review of current gerontechnology applications highlights this gap in the research, noting that there is a dearth of research examining assistive technology geared towards cognitive and psychological needs, with most gerontechnology research focusing on heart disease and diabetes, as evidenced by a systematic review by Barlow and others (2007). Of the research examining gerontechnology to support psychological well-being and quality-of-life, the available technology-based interventions appear to fall into six main categories: *1*) Telemedicine; *2*) Smartphone applications; *3*) Software; *4*) Videogames; *5*) Robots; and *6*) VR. For a more detailed review of the psychological applications of gerontechnology, *see* Vailati-Riboni et al. (2020a).

Benefits and barriers

As outlined above, gerontechnology can be used as a psychological intervention in a variety of ways. Encouragingly, research with varying levels of vigor has highlighted the potential benefits for mental health and well-being linked to gerontechnological interventions (for review, *see* Baker et al., 2018; Buyl et al., 2020; Chen & Schulz, 2016; Lampit et al., 2014; Piau et al., 2014; Vailati-Riboni et al., 2020a). While a full review of the benefits of gerontechnology is beyond the scope of this paper, a growing body of literature points to its potential benefits for social isolation (e.g., Fokkema & Knipscheer, 2007; Tsai et al., 2010; Kahlbaugh et al., 2011; Tsai & Tsai, 2011; Cotten et al., 2013; Aarts et al., 2015), cognitive performance (e.g., Ball et al., 2002; Shatil et al., 2014; Ballesteros et al., 2015; Kim et al., 2015), depression (e.g., Spek et al., 2007; Tsai & Tsai, 2011; Preschl et al., 2012; Dear et al., 2015a; Jøranson et al., 2015; Titov et al., 2015; Firth et al., 2017a), anxiety (e.g., Zou et al., 2012; Mewton et al., 2013; Dear et al., 2015a; Dear et al., 2015b; Firth et al., 2017b), quality of life (Moyle et al., 2013; Broadbent et al., 2014; Vailati-Riboni, 2018; Vailati-Riboni et al., 2020b), and well-being (Cocosila et al., 2009; Thompson et al., 2011; Xie, 2011; Silva et al., 2015). Table 1 provides an overview of findings from a selection of existing reviews evaluating the efficacy of gerontechnology for well-being and mental health.

Gerontechnology is predicted to improve the aging process for older adults; however, its implementation is not without concerns and drawbacks (Kim et al., 2017). Of key importance, despite its potential for improving various aspects of older adults' lives (e.g., social engagement, cognitive engagement, functional independence), this age group continues to show reluctance to engage with technology (Millward, 2003). Older adults' lack of technology uptake is even more pronounced when compared with younger populations, a phenomenon referred to as the "grey digital divide" (Millward, 2003; Nielsen, 2014). Several barriers to gerontechnology use have been identified in the literature. For example, in a study by the Pew Research Center, it was found that skeptical attitudes regarding the benefits of technology use,

TABLE 1 Examples of recent reviews and meta-analyses evaluating gerontechnology aimed at improving mental health and well-being outcomes.

Author, year	Study aims	Studies included, sample size range (n range), average age range (M_{age} range)	Type(s) of gerontechnology reviewed	Study outcomes
Baker et al. (2018)	A systematic review examining the ways that technology is being used to reduce social isolation and increase social participation in older adults	36 studies (16 qualitative, 8 pilot and/or prototype, 2 cross-sectional survey, 3 mixed-method evaluation, 2 social network analysis, 6 quantitative evaluation); n range = 1–388	Information and communication technologies (ICT) facilitating human-computer interaction (e.g., touch-screen technology, social network services, online games, ICT training)	Main findings suggest that ICT for social isolation/ social participation mainly used social network services and touch screen technologies; social outcomes are often poorly defined or not defined; evaluation methodologies were limited and small-scale. Authors point to a need for more rigorous studies examining new forms of technology that target older adults and to clearly define how these technologies support social participation/reduce social isolation
Buyl et al. (2020)	A systematic review summarizing evidence on the effectiveness of e-Health interventions on healthy aging	14 studies (12 RCTS; 2 quasi-experimental controlled trials); n range = 14–1729; M_{age} range = 50–88	e-Health interventions for healthy aging (e.g., Internet-based interventions, teleconsultations smartphone apps, interactive digital games, electronic records)	High heterogeneity in study designs. Risk of bias moderate to high across studies. Findings must be interpreted with caution given low certainty of evidence. Significant positive effects most frequently found for physical activity. e-Health showed moderate impact for improving emotional and mental health (e.g., depression, anxiety), well-being, and quality of life, as well as cognitive outcomes (e.g., memory). Evidence is particularly lacking for social outcomes, with existing evidence on loneliness offering inconclusive results. Better quality evidence needed regarding the effects of e-Health interventions for physiological, psychological, and social components of healthy aging
Chen & Schulz, (2016)	A systematic review examining the effects of information and communication technologies (ICT) at reducing older adults' social isolation	30 studies (6 RCTs, 2 controlled cohort, 4 uncontrolled cohort, 4 cross-sectional, 14 qualitative); n range = 8–5203; M_{age} range = 66–83	Information and communication technologies (ICT) using the internet or Web-based apps on computers, smartphones, computer tablets, or video game systems	High heterogeneity in study designs. 4 of 30 studies were rated as rigorous research. ICT use found to consistently impact social support, social connectedness and social isolation across the 30 studies. Of studies examining loneliness, 15 out of 18 found significant reductions due to ICT use. Effects appear to be short-term. ICT did not significantly impact self-esteem and perceived control over one's life. Qualitative research pointed to four mechanisms through which ICT helped social isolation: *1*) connecting to the outside world; *2*) gaining social support; *3*) engaging in activities of interest, *4*) boosting self-confidence
Lampit et al. (2014)	A systematic review and meta-analysis of the efficacy of computerized cognitive training (CCT) for cognitively healthy older adults	52 studies (52 RCTs), n range = 20–1,398; M_{age} range = 60–82 Eligible studies were RCTs that examined the effects of ≥4 h of CCT on neuropsychological test performance in older adults without dementia or cognitive impairment	Computerized cognitive training (CCT) (i.e., standardized computerized tasks with cognitive rationale, administered *via* personal computers, mobile devices, or gaming consoles)	Cross-study heterogeneity was small (I^2 = 29.92%). No systematic evidence of publication bias. Overall effect size for CCT vs control was small and statistically significant (g = 0.22; 95% CI 0.15–0.29). Small to moderate effect sizes for nonverbal memory (g = 0.24; 95% CI 0.09–0.38), verbal memory (g = 0.08; 95% CI 0.01–0.15), working

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TABLE 1 (*Continued*) Examples of recent reviews and meta-analyses evaluating gerontechnology aimed at improving mental health and well-being outcomes.

Author, year	Study aims	Studies included, sample size range (*n* range), average age range (M_{age} range)	Type(s) of gerontechnology reviewed	Study outcomes
				memory (g = 0.22; 95% CI 0.09–0.35), processing speed (g = 0.31; 95% CI 0.11–0.50) and visuospatial skills (g = 0.30; 95% CI 0.07–0.54). No significant effects were found for executive functioning and attention. Moderator analyses demonstrated that group-based training was more effective than home-based and that three or fewer sessions of CCT per week was more effective
Piau et al. (2014)	Narrative review of current technology appropriate for older adults' home use analyzing the level of effectiveness of gerontechnology at enabling independent living and which devices are designed specifically for frail older adults	184 studies, *n* range = 1–299	Devices targeting social isolation (e.g., visiophonic communication, personal emergency response systems), functional decline (e.g., technology promoting/maintaining autonomy), cognitive disorders and behavioural/psychological symptoms of dementia (e.g., companion-type robots, cognitive orthotics, telemonitoring)	Studies were classified into three categories according to older adult and caregiver needs: *1*) social isolation (k = 19); *2*) functional decline (k = 17); *3*) cognitive disorders and Behavioral and Psychological Symptoms of Dementia (BPSD) (k = 41). Authors found generally positive perceptions of feasibility and efficacy of gerontechnologies targeting these three categories. Limited research was found that specifically targeted frail older adults with even more limited data on use and efficacy of gerontechnology with this population. Methodological weaknesses are prevalent in the research, which limit both generalization and implementation of findings. End-users should be more involved in the development phase of gerontechnologies to improve acceptability and target population usage rate
Vailati Riboni et al. (2020)	A scoping literature review exploring how new technologies are being used to enhance older adult psychological well-being. A thematic content analysis was conducted focusing on the main types of technology-based interventions supporting older adults' quality of life/well-being and the effects of these interventions on cognitive, psychological, and economic outcomes	80 studies	Virtual reality (VR), robots, telemedicine, smartphone applications, software, and videogames	Thematic analysis findings led to classification of papers into the following six categories based on types of technology evaluated: *1*) VR (k = 12); *2*) Robots (k = 24); *3*) Telemedicine (k = 24); *4*) Smartphone Apps (k = 6); *5*) Software (k = 8); *6*) Videogames (k = 6). Definitions, practical examples, and a summary of the technology's effect on older adults' cognitive and psychological outcomes were outlined for each category. Findings suggest that technologically enhanced psychological interventions may be able to improve healthcare accessibility, quality and reduce cost. Additionally, gerontechnology appears to be a promising avenue to help reduce depression, anxiety, and mild cognitive impairment. Older adults' readiness to use new technological tools appears to play a large role in effective implementation of gerontechnology. Further research is warranted as there is currently a dearth of methodological rigorous control group studies and studies investigating social/cultural variables

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difficulties learning to use technologies, and physical challenges were among some of the most frequently cited barriers (Smith, 2014). In a review by Kang and others (2010), obstacles to technology uptake included the tendency for many older adults to feel uncomfortable with new technology, stigma (for e.g., viewing technology as a confession of dependence) and financial concerns. In a focus group study by Vaportzis and others (2017) examining the acceptability of technology and computer tablet use, older adults expressed concerns related to three main categories: *1*) barriers, such as lack of instructions, low confidence, health-related drawbacks, and cost; *2*) disadvantages, such as technology that is too complex or too prolific, feelings of inadequacy, comparison with younger generations, or lack of in-person social interaction, and *3*) skepticism about technology use, in general. Importantly, in a recent review on effective implementation of digital mental health interventions for older adults by Seifert and others (2019), five risks for barriers to gerontechnology use were identified: *1*) lack of experience, social support, and access to digital technology increasing the risk that older adults perceive technology to be exclusionary; *2*) lower use of digital technologies amongst older adults; *3*) retired older adults are not required to use new technologies for their work, potentially reducing their motivation to try new technologies; *4*) lower levels of socialization to technology; and *5*) aging-related increases in cognitive, physical, social, and financial vulnerability leading to greater effort needed to learn to use new technologies. Given the commonly expressed challenges and barriers to gerontechnology use found in the research, effective technologies should be designed to be easily usable by older adults, provide avenues for increased social contact, be easy to fit into the user's daily routine, and provide opportunities for rapid and/or frequent interactions with health providers (Jimison et al., 2008; Kang et al., 2010; Seifert et al., 2019). Finally, and of crucial importance, gerontechnology should be perceived as beneficial by users (Jimison et al., 2008).

Virtual reality

Accordingly, in order to maximize the effectiveness of gerontechnology, it may be useful for research to move beyond conventional telehealth methodologies and examine fresh modalities of mental health provision for older adults, such as VR. VR technology provides computer-generated simulations of three-dimensional environments that the user is able to navigate and interact with in real time (Pratt et al., 1995). VR can be referred to as "immersive" when a user's sensory attention is captured in such a way that they perceive a sense of truly being present in the virtual environment (Slater et al., 1994). VR devices are typically in the form of head-mounted display systems, desktop visual display systems, smartphones, tablets, or other handheld devices (Cherniack, 2011; Lee et al., 2019). For an optimal VR experience, headsets with head-mounted displays using high-end computer processors are needed to facilitate positional tracking, in addition to controlling the immersive virtual environment desktop (Lee et al., 2019). The advent of high-quality standalone headsets, such as the Quest 2 and HTC Vive Focus Plus, now makes it possible to provide quality immersive experiences without the need to connect to a separate powerful computer (Kugler, 2021). VR utilizing 360-degree videos has the ability to virtually transport users, facilitating active exploration and experience of the video from any angle and a perception of immersion in the virtual environment (Riva & Wiederhold, 2020).

In a study by Li and others (2017) where 94 undergraduate students viewed 73 different immersive VR videoclips, VR 360-degree videos were found to induce specific emotions at varying levels of arousal and valence. Additionally, in a series of experiments where participants studied 360° panoramic scenes, either through a sliding window panoramic display or using a VR headset, it was found the 360° VR videos have the potential to create a dynamic interplay between perception and memory that can be used to update and improve the specific features of these cognitive process (Robertson et al., 2016). Furthermore, VR may be able to enhance older adults' motivation to engage in cognitive and/or physically demanding tasks given its capacity to provide fun and enjoyable experiences (Molina et al., 2014; Lee et al., 2019). These findings demonstrate particular promise for addressing mental health issues as they highlight the pathways through which immersive VR may enable lasting psychological and behavioral change.

Efficacy of virtual reality-based well-being interventions in older adults

VR appears to have strong therapeutic potential for use as an intervention for older adults and offers substantial advantages when compared to conventional treatments with respect to accessibility (e.g., to a wider number of clinical stimuli), functionality (i.e., by improving capacity to provide interactions with and tests of "real-life" skills), patient interaction with therapeutic stimuli, standardization of experimental treatments, possibilities for treatment-related virtual environment manipulation, and safety conditions for patients (Cherniack, 2011). Additionally, systematic review evidence suggests that VR may be as effective as traditional treatment methods but may achieve results in shorter periods of time (Mohr et al., 2013; Montana et al., 2020). Notably, preliminary research indicates that VR applications in mental health practice show increased acceptability by older adult patients, as measured *via* the Technology Acceptance Model (Davis, 1989; Benham et al., 2019).

The field of older adult VR is still relatively nascent. However, to-date, scientific research examining the effectiveness of VR interventions for older adults points to various potential benefits for physical, psychological, and social well-being (Hasan and Linger, 2016; Baez et al., 2017; Lee et al., 2019; Montana et al., 2020; Vailati-Riboni et al., 2020). Physical benefits include decreased pain (Benham et al., 2019; Dermody et al., 2020), increased functional strength (Dermody et al., 2020), improved balanced/decreased risk of falls (Bisson et al., 2007; Rendon et al., 2012; Dermody et al., 2020), improved posture (Dermody et al., 2020), and increased physical activity (Miller et al., 2014). Psychological effects include improved cognitive functioning (Optale et al., 2010; Cherniack, 2011; Dermody et al., 2020; Yen & Chiu, 2021), better emotion regulation (Hasan and Linger, 2016; Bornioli et al., 2019; Montana et al., 2020), decreased depression and anxiety (Robert et al., 2016; Yen & Chiu, 2021), creation of positive emotions and enjoyment (Lee et al., 2019), as well as an increased sense of control through environmental mastery and improved capacity to live independently (Lee et al., 2019). While there is less research examining the impact of VR on social outcomes in older adults, it has been hypothesized that VR may have the capability to increase social interaction in this population (Dudley, 2018; Miller et al., 2019). Additionally, VR used as a well-being intervention for older adults appears to have the distinct benefit of meeting more than one health-related need at once, given that VR programs often simultaneously address the physical, psychological, and social needs of the user (Hughes et al., 2017; Dudley, 2018).

Despite the numerous proposed benefits of VR for older adults, the strength of the research base is currently mixed, at best. Meta-analytic and systematic review findings indicate that many study designs are methodologically weak, with high risk for bias (Molina et al., 2014; Lee et al., 2019; Miller et al., 2013; Dermody et al., 2020; Montana et al., 2020; Thach et al., 2020; Skurla et al., 2021; Yen & Chiu, 2021). For example, in a systematic review by Dermody and others (2020) of VR interventions in community dwelling older adults, it was found that all seven of the included studies had small sample sizes ($n \leq 39$), affecting the generalizability of the results. Additionally, none of the papers reviewed received a "high" quality rating (Dermody et al., 2020), based on the grading of recommendations, assessment, development, and evaluation (GRADE) approach to assess overall quality of findings (Higgins & Green, 2011). Similar methodological weaknesses were highlighted in the systematic review of 13 randomized controlled trials (RCTs) by Molina et al. (2014), where small and selective samples were a consistent issue for generalizability of results. Furthermore, none of the studies analyzed reported follow-up analyses, limiting the ability to decipher whether gains made during the intervention period would lead to lasting benefits (Molina et al., 2014). In a systematic review of 14 studies by Miller and others (2013) on the feasibility and effectiveness of VR interventions to enable physical activity in older adults, it was found that the evidence was not strong enough to conclude definitively whether interventions were effective, due to weak study quality and high risk of bias. Additionally, feasibility was reported inconsistently (Miller et al., 2014). A review by Montana and others (2020) pointed to the need for more rigorous RCTs in order to achieve an enhanced understanding of VR *versus* non-VR intervention efficacy. Finally, in the combined meta-analysis and systematic review of RCTs by Yen and Chiu (2021), all 18 studies were found to have moderate risk of bias based on the Cochrane Risk of Bias Rating (Higgins et al., 2011), once again highlighting a need for more rigorous research methodology in the field of VR research.

In addition to methodological limitations, important gaps in study design were identified. Older adults undergo visual and auditory changes as part of the aging process; however, many studies did not consider these age-related changes in their assessments (Dermody et al., 2020). For example, Dermody et al. (2020)'s review of community-based VR interventions for older adult health found that very few studies assessed visual acuity, (Parijat et al., 2014; Parijat et al., 2015) and often excluded participants if they had self-reported or serious visual or sensory impairment (Optale et al., 2010; Parijat et al., 2015; Parijat et al., 2015; Levy et al., 2016). Additionally, none of the studies in their review assessed hearing ability and only three studies measured for cybersickness (Parijat et al., 2015; Parijat et al., 2015; Benham et al., 2019). Furthermore, only one study included a survey question about participants' perceived acceptability of the VR experience (Benham et al., 2019). Without attention paid to auditory and vision-based capabilities, as well as dexterity, older adults may be less likely to accept VR as an intervention. Therefore, further research examining the impact of developmental capacity on VR engagement, as well as design features in VR programs accounting for audio, visual, and physical challenges, is warranted. Notably, none of the studies reviewed by Dermody et al. (2020) integrated gaming technology in the VR system, which could be a potential way to support user engagement and enhance participant enjoyment (Molina et al., 2014). Finally, most studies reviewed examining VR programs for older adults focused on physical health-related interventions, with far fewer VR interventions incorporating an explicit focus on content related to improving psychological well-being (Molina et al., 2014; Parijat et al., 2015; Lee et al., 2019; Dermody et al., 2020; Yen & Chiu, 2021).

Clinical limitations

Several practical factors and challenges must be considered in order to implement VR as a gerontechnology that meets the standard of care for the aged care health sector. Given the mobility and strength issues that many older adults face, they may have trouble setting up VR devices and feel uncomfortable wearing headset devices for maintained lengths of time (Lee et al., 2019). However, with the rise of lightweight headsets such as the HTC Vive Flow the issue of headset weight is becoming less important (Peterson et al., 2021). Unsurprisingly, the majority of research to-date investigates the use of VR for healthy older adults (Dermody et al., 2020). The study of VR interventions for frail or unwell older adults is imperative, particularly due to the potential benefits related to cognitive decline (Optale et al., 2010; Cherniack, 2011; Yen & Chiu, 2021) and fall risk (Bisson et al., 2007; Rendon et al., 2012) that preliminary research in healthy older adults has identified. Additionally, natural age-related developments, such as visual and auditory changes, should be considered when designing VR apps for older adults, as reduced auditory and visual capacity could make VR engagement more difficult for certain older adults (Garrett et al., 2018). Financial barriers must also be considered when implementing VR interventions in aging populations, as VR technology can often be expensive. The economic cost of VR devices may be prohibitive for some older adults; however, due to technological developments, high-quality VR equipment is already becoming less expensive, often costing less than a laptop computer (Segal et al., 2011; Robert et al., 2016). Additionally, private insurance providers are beginning to include coverage for VR in healthcare treatment, further reducing financial barriers to access. For example, Bupa, Australia's largest health insurer, is now covering XRHealth, a company providing VR and augmented reality-based therapeutic applications to the medical industry (XRHealth, 2020). Finally, common barriers to gerontechnology use such as discomfort with technology, lack of training, and skepticism should be addressed when using VR interventions with older adults in order to empower users and improve acceptability and adherence (Vailati-Riboni, 2020).

Nature and virtual reality

Conceptualizations

Keeping in mind the potential barriers to VR usage in older adult populations, one potential avenue for improved mental health and well-being is to design VR programs that incorporate scenes of nature. Exposure to natural settings, as well as perceived connection with nature, have both been shown to be associated with numerous improved psychological health outcomes (for review, *see* Aerts et al., 2018; Capaldi et al., 2014; Hartig et al., 2014, McMahan & Estes, 2015). The notion that natural settings are imperative for human thriving has been explored in the literature for decades (Orians, 1980). For instance, the Biophilia Hypothesis (Wilson, 1984), which is a seminal theory in environmental psychology, posits that human health and well-being is related to connection with our natural environment. Wilson (1984) theorizes that human affiliation with life forms and life-like processes is due to millennia of human evolution in natural surroundings, and the necessity for humans to be in contact with life-like processes in order to survive. Attention Restoration Theory (ART; Kaplan & Kaplan, 1989; Kaplan 1995) provides a theoretical framework to clarify the underlying mechanisms through which nature connection may improve mental health. ART hypothesizes that directed attention is a finite resource that can be restored through exposure and appreciation towards nature *via* "soft fascination"; that is, the attention directed towards interesting stimuli requiring minimal cognitive exertion (Kaplan, 1995). Furthermore, gerontechnology has been theoretically and empirically connected to the impact of the natural environment on healthy aging. For example, through developing appropriate technological interventions that consider the influence of the natural physical environment on well-being as one ages (Fozard, 2012). These hypotheses have been corroborated by a variety of studies (for e.g., Mayer et al., 2009; Nisbet et al., 2011; Roe & Aspinall, 2011; Sadowski et al., 2020; van den Berg et al., 2003; Zelenski & Nisbet, 2014) and reviews (Thompson Coon et al., 2011; Capaldi et al., 2014; Hartig et al., 2014; McMahan & Estes, 2015; Aerts et al., 2018) investigating the relationship between connection with nature and well-being.

Virtual reality technology incorporating natural settings

One way proposed to utilize VR 360-degree video technology most effectively is through the incorporation of natural settings in the VR experience (Depledge et al., 2011; Smith, 2015; Browning et al., 2020). Despite the numerous benefits offered from exposure to *in vivo* nature, many people do not feel comfortable going into natural or "wild" environments, even if they have convenient access to them (Bixler & Floyd, 1999; Browning et al., 2017). It is important to develop and examine technologies, such as VR, that enable frequent, realistic interactions with nature, particularly in the context of older adult health promotion, given that nature may not always be accessible due to mobility restrictions and care needs related to aging, (Depledge et al., 2011; Van Houwelingen-Snippe et al., 2021). VR programs using 360-degree videos of nature are both a convenient and inexpensive way to provide access to nature (Depledge et al., 2011; Smith, 2015). This is particularly important given findings that many of the benefits of nature exposure can be achieved through VR headsets providing visual and auditory sensory information (Browning et al., 2020). Preliminary research comparing interaction with real-life nature to VR-based nature shows evidence that VR nature may provide similar benefits, although there is a lack of clarity to the extent that this comparison holds true, with some studies showing that the impacts of VR-based nature may be less beneficial for mood (Kjellgren & Buhrkall, 2010; Annerstedt et al., 2013; Calogiuri et al., 2018; Browning et al., 2020).

While the research field examining the impacts of VR-based natural environments is still relatively new, a growing body of literature points to the therapeutic efficacy of 360-degree nature videos (Valtchanov, 2010; Maples-Keller et al., 2017; Jerdan et al., 2018; White et al., 2018). For example, nature-based VR videos have been evidenced to rapidly improve mood in experimental studies of healthy, community-based young and middle-aged adults (Anderson et al., 2017) and university students (Valtchanov, 2010; Schutte et al., 2017; Yu et al., 2018). Anderson and others' (2017) study of 18 young to middle-aged adults found that VR nature scenes 15-min in length improved both objective (electrodermal activity and heart-rate variability) and subjective (Positive and Negative Affect Schedule; Watson et al., 1988) affect. Yu et al. (2018) corroborated these findings in their study of psychological responses to 9-min VR nature videos in 30 healthy young adults, but did not find significant effects for physiological responses. Both Schutte et al. (2017) and Valtchanov (2010) reported that university student responses to short immersive VR-based nature videos indicated benefits for subjective psychological mood levels. Valtchanov (2010) also found objective improvements to relaxation *via* skin-conductance and heart rate.

The benefits to well-being conferred from 360-nature videos appear to extend to improvements in cognitive functioning (Gerber et al., 2017; Chung et al., 2018) and reductions in physiological levels of stress (Gerber et al., 2017; Hedblom et al., 2019). In Chung and others (2018) study of 40 healthy young adults, preliminary support was provided for the capability of 360-degree nature videos to restore attention, through subjective (Perceived Restorativeness Scale; Hartig et al., 1997) and objective measures (*via* event-related potential). Hedblom and others (2019) experimental study compared the effects of 360-degree virtual visual stimuli of urban environments, forests, and parks, with congruent olfactory stimuli (i.e., city and nature odors) and auditory stimuli (i.e., noise and bird songs) on physiological stress levels in 154 healthy young adults. Their findings indicated that the virtual park and forest provided significant stress reductions, but not the urban area (Hedblom et al., 2019). In addition to community settings, 360-degree VR nature videos show potential for improving attentional capacity and reducing physiological measures of stress in intensive care unit (ICU) settings, based on findings from 37 healthy younger and older adults with ages ranging from 20 to 85 (Gerber et al., 2017).

Despite preliminary support for VR-based nature videos on psychological well-being, several methodological and design limitations in the current scientific literature should be mentioned. The vast majority of reviewed studies examined healthy, younger or middle-aged adults with fairly small sample sizes. This significantly impacts the ability to generalize the results of these studies and it remains unclear whether the effects found would be the same in exclusively older adult or clinical populations. Many studies investigated both physiological and psychological outcomes, which was a methodological strength. However, most studies did not assess longitudinal outcomes of nature-based VR inductions and interventions, instead relying on single-time point evidence. Further studies are needed to clarify the durability of affective, cognitive and stress level improvements associated with 360-degree VR nature videos.

Nature-based virtual reality technology in older adults

To-date, empirical research on nature-based VR interventions for older-adult well-being is extremely limited with only ten published articles found when conducting the literature search for this review. However, of these 10, only eight specifically focus on nature-based VR experiences for older adults (Banos et al., 2012; Bruun-Pedersen et al., 2014; Bruun-Pedersen et al., 2016; Bornioli et al., 2018; Moyle et al., 2018; Reynolds et al., 2018; Bornioli et al., 2019; Ludden et al., 2019), with the remaining two including older adults in their samples, but not exclusively studying this age group (Bornioli et al., 2018; Bornioli et al., 2019). Most studies focus on healthy, non-clinical samples (Banos et al., 2012; Bruun-Pedersen et al., 2014; Bruun-Pedersen et al., 2016; Bornioli et al., 2018; Bornioli et al., 2019), but three focused on older adults with symptoms of cognitive decline or dementia (Moyle et al., 2018; Reynolds et al., 2018; Ludden et al., 2019). Study findings are presented in Table 2 according to reference, sample, VR technology, VR environment, aims, design, measures, and results.

For example, in a study by Banos et al. (2012) the ability of VR-based nature walks to enhance feelings of positive mood and relaxation in 18 healthy older adults was explored. It was found that the virtual environments provided significant increases in joy and relaxation, and significant decreases in sadness and anxiety (Banos et al., 2012). Additionally, participants reported low difficulty of use along with high levels of satisfaction and sense of presence (Banos et al., 2012). However, this study used a small sample size with a non-clinical population, limiting generalizability of findings. Furthermore, the study examined only two sessions with the VR environment. In order to draw more robust conclusions, studies examining multiple nature-based VR sessions should be conducted, as it is likely that this will improve older adults' comfortability with the VR interface, further clarifying the impact of the intervention itself on mood (Banos et al., 2012).

The impact of interactive screens with virtual nature scenes attached to exercise bicycles has been examined for potential benefits for enjoyment and self-efficacy in healthy older adults living in retirement homes (Bruun-Pedersen et al., 2014; Bruun-Pedersen et al., 2016). Results indicated that participants exercised for longer, experienced more excitement and felt an

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TABLE 2 Examples of empirical studies of nature-based VR interventions for older-adult mental health and well-being.

Author, year (Country)	Participants	Virtual technology	Virtual environment	Study aims	Study design	Study measures	Results
Banos et al. (2012) (Spain)	Healthy older adult sample; $n = 18$; 77.8% female; age range 58–79 ($M = 66.94$; $SD = 5.52$)	Non-immersive: desktop computer	Two distinct computer simulated virtual natural environments (VEs) (e.g., leafy plants, green fields, blue skies) and designed to elicit positive emotions (joy VE and relaxation VE)	Investigated the efficacy, user satisfaction, and sense of immersion of mood induction procedures using VR for older adults	Non-controlled; within-subject; pre-post	State-Trait-Anxiety-Inventory (STAI-S); Geriatric Depression Scale-15 (GDS-15); Visual Analogical Scale (VAS); General Mood State (GMS); Level of Satisfaction with the VEs (LS); Level of Difficulty (LD); Sense of Presence (PR)	After relaxation VE (RVE) and Joy VE (JVE), significant increases in joy (RVE: $F = 12.91$, $p = 0.00$, $\mu = 0.54$; JVE: $F = 9.33$, $p = 0.00$, $\mu = 0.40$) and relaxation (RVE: $F = 6.77$, $p = 0.03$, $\mu = 0.38$; JVE: $F = 10.33$, $p = 0.00$, $\mu = 0.43$), significant decreases in sadness (RVE: $F = 3.87$, $p = 0.07$, $\mu = 0.26$; JVE: $F = 15.00$ $p = 0.00$, $\mu = 0.52$) and anxiety (RVE: $F = 4.53$, $p = 0.05$, $\mu = 0.29$; JVE: $F = 7.99$, $p = 0.01$, $\mu = 0.36$). Low levels of user difficulty and high levels of satisfaction, sense of presence
Bornioli et al. (2018) (United Kingdom)	Mixed community and university sample; $n = 269$; 69.1% female; age range 18–67 ($M = 31.69$; $SD = 13.63$)	Non-immersive: viewed on computer monitor; videos filmed on GoPro HERO 35 mm	Five distinct virtual environment conditions with mixture of urban and natural surroundings	Assessed the affective outcomes associated with virtual urban walking settings	Mixed-methods; within-between subjects; pre-post	University of Wales Institute of Science and Technology Mood Adjective Checklist (UWIST MACL); Perceived Restorativeness Scale (PRS); Environmental perceptions (aesthetics and interestingness)	Walking in natural environments and high-quality aesthetic urban environments resulted in improved affective experiences ($F(4, 265) = 25.774$, $p < 0.001$, $\eta_p^2 = 0.283$)
Bornioli et al. (2019) (United Kingdom)	Mixed community and university sample; Quantitative sample: $n = 384$; 70.1% female; age range 18–67 ($M = 35.01$; $SD = 13.89$); Qualitative sample: $n = 14$; 57.1% female; age range 18–53 ($M = 31.69$; $SD = 8.63$)	Non-immersive: viewed on computer monitor; videos filmed on GoPro HERO 35 mm	Five distinct virtual environment conditions with mixture of urban and natural surroundings	Examined relationship between affective walking experience, intentions, and characteristics of built *versus* natural environments	Mixed-methods; within-between subjects; pre-post; quantitative questionnaires with full sample; interviews with qualitative subset sample	Quantitative: University of Wales Institute of Science and Technology Mood Adjective Checklist (UWIST MACL); Environmental perceptions (aesthetics and interestingness); Qualitative: Semi-structured interviews	Affective experiences of walking based on virtual environment simulations influenced walking intentions ($F(8, 206) = 11.113$., $MSE = 88.906$, $p < 0.001$, $R^2_{adj} = 0.350$). Safety, comfort, and moderate sensory stimulation are important factors for the virtual walking experience
Bruun-Pedersen et al. (2014) (Denmark)	Nursing home residents; $n = 10$; 80.0% female; age range 66–97 ($M = 82.9$; $SD = 9.1$)	Semi-immersive: Samsung LED monitor connected to a manuped stationary exercise bike	Computer simulated environment Summer-time countryside based on a trip along a gravel path going around a lake	Explored if a VR-type manuped exercise shows promise as an assistive technology for retirement home residents	Qualitative; semi-structured *in-situ* interviews	Evaluation videotaping; qualitative semi-structured interview	Participants were enthusiastic about VR technology, nature scenes and felt that it improved their exercise experience, as well as their individual impressions about technology

(Continued on following page)

TABLE 2 (*Continued*) Examples of empirical studies of nature-based VR interventions for older-adult mental health and well-being.

Author, year (Country)	Participants	Virtual technology	Virtual environment	Study aims	Study design	Study measures	Results
Bruun-Pedersen et al. (2016) (Denmark)	Nursing home residents; $n = 9$; 100% female; age range 69–101 ($M = 85$; $SD = 10.2$)	Immersive: Oculus Rift Development Kit 2 (DK2) Head-Mounted Display (HMD). Virtual environment implemented with Unity3D 4.6 PRO.	Four distinct virtual environments (Country Side, Mountain Top, Lake Park, Winter Forest) were used and followed a structured approach linked to nature-based trail exploration in VR.	Evaluated effect of immersive VR compared to less immersive VR on older adults' sense of presence, level of intrinsic motivation to exercise, and exercise user experience	Controlled study; within-between subjects; pre-post	Slater-Usoh-Steed Presence Measure (SUS); Intrinsic Motivation Inventory (IMI); video recordings for qualitative areas of interest in the virtual environment	Increasing immersive presence through immersive VR headsets increased participants' sense of presence (Condition A = 0.37 ± 2.2; Condition B = 0.81 ± 1.9) but had only minimal effects on intrinsic motivation to exercise (Condition A = 4.8 ± 1.7; Condition B = 5.6 ± 2.1). HMDs provided positive experiences for older adults but might not be ready to be used unassisted in exercise contexts
Ludden et al. (2019) (Netherlands)	Older adults with dementia residing at assisted living homes	Semi-immersive: projected *via* Beamer with use of a Kinect camera to project participant shadows onto the wall	Computer simulated virtual nature scenes with fascinating elements (e.g., trees, cloudscapes, flocks of birds)	Investigated whether VR-based nature scenes promote social engagement, relaxation and decrease restlessness	Case study	Interviews with assisted living care personnel	Interviews with care personnel indicated VR nature scenes were successful in promoting positive, relaxed atmospheres and increasing social engagement
Moyle et al. (2018) (Australia)	Older adults with dementia residing at assisted living homes; $n = 10$; 70.0% female; age range N/A ($M = 89.0$; $SD = 5.0$)	Semi-immersive: The Virtual Reality Forest is projected onto large, interactive screen. Uses video game technology (e.g., motion sensors, vivid graphics) to create interactive/immersive environment. Microsoft Kinect ® motion sensors are used for participants to interact with scene using hands and arms	Virtual Reality Forest includes computer simulated images of nature (e.g., river with bridge, trees and flowers) and background nature audio (e.g., bird calls)	Measured and described the effectiveness of the Virtual Reality Forest on engagement, apathy, and mood states for residents with dementia and their experiences using VR in their residence (from perspective of residents, staff and family)	Mixed-methods; non-controlled; pre-post	Observed Emotion Rating Scale (OERS); Person-Environment Apathy Rating Scale (PEAR); Types of Engagement; Semi-structured interviews	Residents perceived the Virtual Reality Forest to have a positive effect. Significant increases in pleasure ($p = 0.008$), alertness ($p < 0.001$). Also, greater levels of fear/anxiety during VR compared to normative samples ($p = 0.016$)
Reynolds et al. (2018) (USA)	Older adults with dementia residing at assisted living homes; $n = 14$; 57.2% female; mean age (female) = 85.5 ($SD = 2.1$); mean age (male) = 84.7 ($SD = 5.8$)	Semi-immersive: Large TV screen framed by shutters to imitate a window in the room	Fixed-angle unedited nature video (waterfall, mountains and naturally occurring sounds)	Tested whether virtual nature reduces stressful emotions (e.g., agitation, anxiety) among individuals with dementia	Counterbalanced crossover; pre-post	Observed Emotion Rating Scale (OERS); Agitated Behavior Scale (ABS); Heart Rate *via* Pulse Oximeter; noted participant comments about program	Heart rate declined significantly compared to the control ($p = 0.012$); anxiety ($p = 0.268$) and pleasure ($p = 0.370$) showed greater improvements compared to control, but difference was not statistically significant. Agitation ($p = 0.003$) and anger ($p = 0.028$) significantly decreased in both conditions

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increased sense of control regarding their ability to engage in exercise (Bruun-Pedersen et al., 2014). However, these studies had small sample sizes ($n \leq 15$), were conducted with healthy older adults, and did not use control groups, making findings challenging to generalize (Bruun-Pedersen et al., 2014; Bruun-Pedersen et al., 2016).

In an example of a study examining the potential use of VR-based nature videos for older adults with dementia, Ludden et al. (2019) conducted a series of case studies based at a residential care home in Sweden. Preliminary feedback from study participants and care home staff indicated acceptability and beneficial effects for mood and relaxation. However, due to the study design, the findings are once again challenging to replicate or generalize due to small sample size and lack of experimental design.

Taken together, there is clearly much work to be done to build the quality of evidence examining the impacts of VR-based nature environments for older adult well-being. While the quality of the empirical evidence is currently weak, qualitative findings indicate strong potential for clinical and practical benefits of VR-based nature interventions for the successful aging of older adults. This is particularly promising given the challenges that older adults may be faced with when trying to access nature in real life. Further research with longitudinal RCTs in both clinical and non-clinical populations is warranted to elucidate the feasibility, level of efficacy and mechanisms through which these interventions operate.

Mindfulness and virtual reality

Conceptualizations: Mindfulness and virtual reality

There are numerous definitions and frameworks for understanding mindfulness (for in-depth reviews of prevailing conceptualizations, *see*: Bodhi, 2011; Dunne, 2015; Gethin, 2011; Hart et al., 2013; Khoury et al., 2017). As a construct, the origins of mindfulness are derived from Buddhist tradition, where mindfulness is described as both the ability to remember past experiences in order to facilitate a deeper sense of purpose and awareness (Anālayo, 2003; Bodhi, 2011) and the capability to comprehend what is occurring the present moment (Brown et al., 2007; Bodhi, 2011). In recent years, mindfulness has been increasingly researched within the context of Western science, as is evidenced by growth in the number of mindfulness-related publications during the past four decades (Google Scholar, 2021). Perhaps the most prevalent westernized understanding of mindfulness is Kabat-Zinn's (1994) conceptualization, where mindfulness is described as a non-judgmental, intentional awareness of the present moment. Mindfulness has also been theorized to be a socio-cognitive ability that allows individuals to notice and draw novel distinctions between objects, people, feelings, thoughts, or experiences and is described as the opposite of "mindlessness" (Langer, 1989; Langer and Moldoveaunu, 2000). Mindlessness is conceptualized as the state of being stuck in previously developed cognitive categories which prevents us from fully engaging with the experience at hand (Langer, 1989). Langer's mindfulness paradigm is particularly interesting in the context of gerontechnology given the many barriers that older adults may face when attempting to use or integrate technology into their daily routines. A final important western conceptualization of mindfulness, which has been developed in more recent years as a way to reconcile different conceptual approaches, is that of embodied mindfulness (Khoury et al., 2017). Embodied mindfulness is embedded in both Buddhist philosophy and neurobiology and considers mindful consciousness as an interaction between the mind, body, and outside world (Khoury et al., 2017). The notion of embodied mindfulness becomes increasingly relevant in the context of immersive VR given the overlap between effectiveness of VR technology due to the concept of presence (i.e., the feeling of "being there" in one's body) and the notion of embodied mindfulness as a skill or ability that includes elements of attention, awareness, and acceptance of the mind, body, and mind-body connections (Slater et al., 1994; Khoury et al., 2017). The concepts of embodied mindfulness and presence also connect to general design considerations in gerontechnology, because technologies that incorporate understanding of older adult users' intentions and perceptions (e.g., understandability of a game or training structure, graphic realism, engaging storytelling) are generally experienced as more acceptable and easier to integrate into daily life (Triberti and Riva, 2016; Tuena et al., 2020). It is likely that the sense of mindful presence that these design elements facilitate allows for more potent gerontechnology interventions, such as VR (Tuena et al., 2020).

It has been theorized that some of the effectiveness of VR interventions is due to enhancing perceptions of mindfulness. For instance, through immersive VR's capacity to capture participants' attention and provide users the illusion of "being there" in the 3D computer generated environment, VR interventions may be particularly effective at incorporating mindfulness-based activities (Slater et al., 1994). By providing users with an interesting and engaging setting to practice mindfulness (e.g., simulated natural settings), limiting distractions from the real world, and increasing a sense of presence, VR may facilitate mindfulness practice (Navarro-Haro et al., 2017). As previously described, in the context of VR, "immersion" refers to the capability of a technical system to deliver an encompassing and convincing environment that a user is able to interact with, whereas the concept of "presence" refers to the experience of feeling and behaving as if one is actually in the virtual environment (Sanchez-Vives & Slater, 2005). Both of these sensations appear to have considerable overlap with elements of mindfulness in that they require the user to be present in the here and now and pay some level of attention to both their bodily sensations and environmental perceptions. Research demonstrates that the more immersive a VR intervention is, the more likely that users will endorse acceptability of the VR experience and report benefits (Riva et al., 2016). Additionally, if the VR experience is immersive enough, the VR user may have the perception that they are present in the virtual world or virtual body due to the alternation of cognitive factors that regulate the experience of body and physical space *via* perceptual information. In the context of VR this perception can also be referred to as "embodiment" (for a more detailed review of this theory, *see* Riva et al., 2015). Thus, it appears that mindfulness and immersive VR have the potential to operate in a bi-directional pathway, with increased mindfulness leading to augmented awareness and attention to the VR experience, and enhanced immersion in VR experiences leading to increased levels of mindfulness. Given the potential for mindfulness to enable older adults to approach technology with curiosity and openness to explore the unknown, improve engagement (Bercovitz & Pagnini, 2016), and the potential for VR to activate mindful experiences, VR applications that incorporate elements of mindfulness might be particularly useful in the context of gerontechnology interventions to support older-adult mental health and well-being.

Mindfulness-based interventions

Mindfulness-based interventions (MBIs) are behavioral interventions that teach mindfulness, following a mind-body medicine view of health by integrating physical, cognitive-affective, behavioral, and social components (Kabat-Zinn, 2013; Khoury et al., 2017; Khoury, 2018). MBIs have demonstrated efficacy for improving psychological well-being and reducing stress in non-clinical populations, as well as for a large range of psychological and physical disorders in clinical populations (for more in-depth review, *see* Carletto et al., 2020; Carrière et al., 2018; Goldberg et al., 2018; Hofmann et al., 2010; Howarth et al., 2019; Khoury et al., 2013; Khoury et al., 2015; Poissant et al., 2019).

MBIs for older adults

A growing body of evidence suggests that MBIs have beneficial effects for older adults' well-being at the psychological, cognitive, and physical levels. Regarding older adults' psychological well-being, findings from exploratory studies and RCTs show decreased levels of stress, anxiety, worry, depression, negative self-focus, as well as increased effective coping strategies and resilience following MBIs when compared to control conditions (Young & Baime, 2010; Foulk et al., 2014; Lenze et al., 2014; Labbé et al., 2016; Perez-Blasco et al., 2016; Franco et al., 2017; Wetherell et al., 2017; Torres-Platas et al., 2019; Dikaois et al., 2020). With respect to cognitive well-being, cross-sectional studies have demonstrated associations between executive function and trait mindfulness, with reductions in stress mediating this relationship (Fiocco & Mallya, 2015). Furthermore, evidence from RCTs suggests significant improvements in older adults' executive functioning following participation in MBIs (Moynihan et al., 2013). Concerning empirical support for the effects of MBIs on physiological well-being, participation in MBIs has been linked to benefits for immune response functionality, suggesting improved cellular level health post MBI participation (Gallegos et al., 2013; Ng et al., 2020). These findings are especially notable given that many older adults experience dysregulation of the immune system, which is associated with numerous adverse outcomes such as augmented vulnerability to infectious, autoimmune, cardiovascular, metabolic, and neurodegenerative diseases, and is worsened by chronic stress (Gouin et al., 2008; Müller et al., 2019). Findings from systematic reviews and meta-analyses further corroborate this evidence, with support found for MBIs' ability to enhance positive mood, decrease symptoms of anxiety and depression, improve sleep quality and decrease chronic insomnia (Hazlett-Stevens et al., 2019). Additionally, meta-analytic and review findings indicate substantial support for the beneficial effects of MBIs on memory, and executive functioning, in particular, processing speed, sustained attention accuracy, and subjective attentional control (Chan et al., 2019; Hazlett-Stevens et al., 2019; Zainal & Newman, 2020).

However, these findings are not without limitations. Research investigating the efficacy of MBIs in exclusively older adult clinical populations is still minimal, with only seven RCT investigations identified to-date (Hazlett-Stevens et al., 2019). Hazlett-Stevens and others (2019) suggest that further research in specifically older adult clinical samples is needed in order to verify whether findings from research in mixed samples are actually generalizable to older adults. Additionally, findings from Hazlett-Stevens et al. (2019) point to a dearth of research examining the impacts of MBIs on comorbid conditions in older adults. Methodologically rigorous research examining the common psychiatric and medical comorbidities found in older adult patients is warranted. Additional gaps in the evidence-base include lack of measurement of quality of life and coping related to health conditions, as well as overwhelmingly westernized, educated, industrialized, rich and democratic (WEIRD) samples, which is a systemic problem biasing the psychology research field, in general (Henrich et al., 2010; Nielsen et al., 2017). Furthermore, despite the potential advantages of practicing mindfulness-based activities, many older adults who stand to benefit do not practice due to the demanding nature of developing mindfulness skills (e.g., traditional mindfulness practices may lead to states of dormancy in novice trainees which can be aversive and counter to the aims of mindful presence and attention). Unsurprisingly, this can lead to high rates of attrition during MBIs (Geiger et al., 2016).

MBIs using virtual reality

Given the challenges for some older adults to maintain alertness when beginning mindfulness practices, and the related high levels of attrition in MBIs for older adults, facilitating mindfulness training through a VR platform could be an optimal way to help engage novice trainees, due to its ability to facilitate a sense of alertness, engagement, and presence (Slater et al., 1994; Navarro-Haro et al., 2017). Furthermore, VR programs that incorporate scenes of nature may be particularly effective at boosting user engagement with MBIs given that untrained meditators are more able to access soft fascination in restorative environments, such as nature (Kaplan, 2001; Schutte & Malouff, 2018). Preliminary findings highlight that VR is a promising technology to support MBIs, with evidence pointing to increases in well-being, self-compassion, and adherence among participants (Tong et al., 2015; Navarro-Haro et al., 2016; Navarro-Haro et al., 2017; Navarro-Haro et al., 2019; Seabrook et al., 2020; Modrego-Alarcón et al., 2021). Additionally, VR-based MBIs appear to lead to increased state (i.e., in-the-moment) mindfulness in both new and experienced meditators (Navarro-Haro et al., 2017; Chandrasiri et al., 2020), with RCT evidence suggesting that VR MBIs are as effective as in-person MBIs at cultivating state mindfulness (Chandrasiri et al., 2020). Furthermore, empirical findings indicate that VR-based MBIs incorporating scenes of nature may be effective at reducing pain (Tong et al., 2015) and improving cognitive functioning and satisfaction with life (Cikajlo et al., 2016) in clinical and non-clinical populations. The research field examining the effects of MBIs based in VR is still in its relative infancy; therefore, significant gaps in the literature exist. There are very few studies investigating the efficacy of MBIs delivered *via* VR, and with the exception of Cikajlo et al. (2016), who investigated a VR-based MBI 8-week in length, and Modrego-Alarcón et al. (2021) who investigated a mindfulness-compassion VR intervention 6-week in length, the existing VR-based MBI studies were either very short (e.g., one to two brief mindfulness sessions), or part of therapeutic interventions that did not focus exclusively on mindfulness, for example using Dialectical Behavior Therapy ® (Linehan, 1993; Navarro-Haro et al., 2016; Navarro-Haro et al., 2017; Navarro-Haro et al., 2019). Finally, to-date, no study has investigated MBIs delivered *via* VR exclusively for older adults. Current literature in related disciplines suggest benefits for this population; however, there is a need for empirical evidence to verify this claim. Examples of findings from studies of VR-based MBIs are presented in Table 3 according to reference, sample, VR technology, VR environment, aims, design, measures, and results.

Self-compassion and virtual reality

Conceptualizations: Self-compassion and virtual reality

Comparable to mindfulness, there are many differing conceptualizations of self-compassion from both eastern and western perspectives (Khoury, 2019). As a practice, self-compassion originates from Buddhist traditions (Shonin et al., 2014) and was introduced to western psychology and research by clinical psychologist Paul Gilbert and research psychologist Kristin Neff (Neff, 2003; Neff, 2004; Gilbert, 2006). There is much debate regarding the definition and measurement of self-compassion (Muris et al., 2016; Cleare et al., 2018; Coroiu et al., 2018) and issues regarding a lack of a conceptualization that includes both the eastern Buddhist origins and western definitions (Davidson et al., 2002; Muris et al., 2016; Strauss et al., 2016; Zeng et al., 2016). While a full review of self-compassion and its Buddhist and westernized conceptualizations is beyond this paper, it is important to be aware of the influence that Buddhist concepts have had on the interpretation of self-compassion in western psychological science. Following a westernized conceptualization, self-compassion can be described as relating to oneself with a kind and forgiving attitude (Neff & Vonk, 2009) and involves noticing distress, as well as building understanding that one's suffering is part of the human condition (Neff, 2003).

As previously described, embodiment in the context of VR refers to the illusion that an individual's real body is the life-sized virtual body that is observable to them in the virtual environment (Slater et al., 2010; Petkova et al., 2011). Embodiment appears to alter physiological and psychological perspectives. For example, shifting an individual's perception of the size of their body (e.g., adults believing their body is the size of a simulated child's body) as well as modifying racial attitudes when perceiving embodiment in a simulated body with a different skin color than the VR user's actual body (Banakou et al., 2013; Peck et al., 2013; Martini et al., 2014; Maister et al., 2015). It is theorized that virtual embodiment may enhance self-compassion in individuals with elevated levels of self-criticism (Falconer et al., 2014) and research is beginning to investigate the effects of embodying virtual adult and child bodies, and interacting compassionately with those bodies, on decreasing self-criticism and depressive symptoms (Baghaei et al., 2019; Falconer et al., 2016; Falconer et al., 2014). Cebolla and others (2019) highlights the importance of imagery skills in self-compassion, as many techniques for increasing compassion in therapeutic settings require mental imagery abilities that induce and train positive mental states (Pearson et al., 2013; Cebolla et al., 2019). If individuals struggle to maintain imagery during meditative compassion-practice this can lead to challenges reaching feelings of compassion and can discourage participants from continuing with the necessary training needed to foster compassion-based skills and positive qualities (Cebolla et al., 2019). To overcome attrition related to lack of ability to sustain mental imagery, VR can be very useful as it enables the construction, maintenance, inspection, and transformation of mental images and can be considered an advanced imagery system that is as effective as reality at inducing emotional, cognitive, and behavioral responses (Day et al., 2004). Self-compassion training *via* VR programs could be especially useful for aging populations (Tavares et al., 2020). In particular, given research indicating that older adults may respond to gradual deterioration in physical and cognitive resources with self-criticism by blaming themselves for these

TABLE 3 Examples of empirical studies of mindfulness-based VR interventions for mental health and well-being.

Author, year (Country)	Participants	Virtual technology	Virtual environment	Study aims	Study design	Study measures	Results
Chandrasiri et al. (2020) (Australia)	Mixed community and university sample; $n = 32$; 50.0% female; age range 18–65 ($M = 27.25$; $SD = 6.04$)	Immersive: Oculus Rift head-mounted display	360-degree VR video of an ocean coastal area; meditative audio	Evaluated whether a brief VR-based mindfulness intervention enhances mindfulness in novice meditators	Two-arm RCT; within-between subjects; pre-post	Toronto Mindfulness Scale (TMS)	Participants in VR mindful ness condition experienced increases in state mindfulness ($t(15) = -5.20$, $p < 0.05$). VR mindfulness was not signifi cantly more effective than conventional mindfulness at increasing state mindfulness levels $t(30) = 1.32$, $p = 0.195$
Cikajlo et al. (2016) (Slovenia)	Mix of traumatic brain injury (TBI) outpatients and community adults; $n = 8$; four workers (age range 27–40); four TBI outpatients (age range 24–48)	Immersive: Samsung GearVR head-mounted display	8-week Mindfulness Based Stress Reduction (MBSR) within virtual room. Included two different 3D video sceneries (lake, river), and one VR environment (Mountain View)	To examine the efficacy of a modified MBSR program delivered through VR at enhancing mindfulness, life satisfaction and cognitive status	Non-controlled; pre-post-follow-up	Mindful Attention Awareness Scale (MAAS); Satisfaction with Life Scale (SWLS); Mini Mental State Examination (MMSE)	Researchers reported individual scores and changes in scores. Improvements were noted in satisfaction with life scores for TBI patients; how ever, limited change occurred for mindfulness levels
Modrego-Alarcón et al. (2021) (Spain)	University students; $n = 280$; 78.9% female; Mean age = 22.25 ($SD = 5.74$)	Immersive: Samsung GearVR goggles	Series of mindfulness-or compassion-based exercises using different virtual environments paired to the activity and guided by audio instructions (e.g., observing leaves falling from tree)	Tested efficacy of VR-based mindfulness-compassion programs in the Spanish university context at reducing stress levels	Three-arm RCT; between-group; pre-post-6 months follow-up	Perceived Stress Scale (PSS); State-Trait Anxiety Inventory (STAI); Positive and Negative Affect Schedule (PANAS); Utrecht Work Engagement Survey Scale-Students (UWES-S); Maslach Burnout Inventory-Student Survey (MBI-SS); Emotion Regulation Questionnaire (ERQ); Five-Facet Mindfulness Questionnaire (FFMQ); Self-Compassion Scale (SCS)	VR mindfulness-compassion ($B = -2.77$, $d = -0.72$, $p = 0.006$) and conventional mindfulness-compassion ($B = -2.44$, $d = -0.59$, $p = 0.014$) were more effective than the relaxation condition at improving stress, as well as many of the secondary outcomes. Long-term effects of mindfulness training were mediated by mindfulness ($ab = -1.09$, 95% CI [−2.20 to −0.24]) and self-compassion ($ab = -1.14$, 95% CI [−2.45 to −0.09]). Treatment adherence was highest in the VR mindfulness group (Fisher $p < 0.001$)
Navarro-Haro et al. (2016) (Spain)	Participant diagnosed with borderline personality disorder (BPD); $n = 1$; female; 32-year-old	Immersive: Kaiser Electro-Optics VR goggles	3D computer-generated environment (e.g., river with trees, boulders, and mountains) with DBT ® meditation audios, with one audio paired with what patient was observing	Explored feasibility and clinical potential of VR-facilitated Dialectical Behavior Therapy (DBT)® mindfulness skills learning in a patient with BPD	Case-study; within-subject; pre-post	DBT diary card; Kentucky Inventory of Mindfulness Skills-Short Form (KIMS-Short) interviewed patient about experience with VR program	VR mindfulness sessions reduced urges to commit suicide, self-harm, quit therapy, use substances, and negative emotions. VR mindfulness was well-accepted by patient
Navarro-Haro et al. (2017) (Spain)	Attendees of 3rd International Meeting on Mindfulness; $n = 44$; 63.6% female; age range 21–69 ($M = 45.32$; $SD = 13.20$)	Immersive: Oculus Rift DK2 VR goggles with head mounted display and head tracking	DBT® VR *MindfulRiverWorld* 3D computer-generated environment (e.g., river with trees, boulders, and mountains) with DBT ® meditation audios	Explored feasibility, acceptability, potential benefits of VR-facilitated Dialectical Behavior Therapy (DBT)® mindfulness skills learning	Non-controlled; within-subject; pre-post	Meditation frequency (MINDSENS); Emotional state visual analog scale; Mindful Attention Awareness Scale (MAAS); Sense of Presence questionnaire;	Participants reported significant decreases in sadness ($t(42) = 3.250$, $p < 0.01$, $SE = 0.16$, $d = 0.44$), anger ($t(42) = 2.048$, $p < 0.05$, $SE = 0.13$, $d = 0.28$), anxiety

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TABLE 3 (*Continued*) Examples of empirical studies of mindfulness-based VR interventions for mental health and well-being.

Author, year (Country)	Participants	Virtual technology	Virtual environment	Study aims	Study design	Study measures	Results
			paired to what participants were observing	in a non-clinical sample of individuals who already practice mindfulness		Credibility/Expectancy rating adaptation; Independent Television Company SOP Inventory (ITC-SOPI)	($t(42) = 2.818$, $p < 0.01$, $SE = 0.24$, $d = 0.51$), increases in relaxation (t(42) = 3.681, $p < 0.01$, $SE = 0.25$, $d = 0.68$) and state mindfulness ($t(42) = 4.431$, $p < 0.001$, $SE = 0.20$, $d = 0.75$) post-VR. High participant acceptance and immersion levels
Navarro-Haro et al. (2019) (Spain)	Participants diagnosed with generalized anxiety disorder (GAD); $n = 39$; 76.9% female; Mean age = 45.23 ($SD = 11.23$)	Immersive: Oculus Rift DK2 VR goggles with head mounted display and head tracking	DBT® VR *MindfulRiverWorld* 3D computer-generated environment (e.g., river with trees, boulders, and mountains) with DBT ® meditation audios paired to what participants were observing	Evaluated the effect of mindfulness training using VR (MBI+VR) and conventionally administered (MBI) to reduce GAD symptoms	Two arm RCT; within-between-group; pre-post	Mini International Neuropsychiatric Interview (MINI); General Anxiety Disorder-7 items (GAD-7); Hospital Anxiety and Depression Scale (HADS); Five Facet Mindfulness Questionnaire (FFMQ); Difficulties of Emotion Regulation Scale (DERS); Multidimensional Assessment of Interoceptive Awareness (MAIA); Independent Television Company SOP Inventory (ITC-SOPI); Emotional state visual analog scale; Sense of Presence questionnaire	Both groups had significant improvements in GAD symptoms (MBI: $B = -5.70$, $p < 0.001$, $d = -1.36$; MBI+VR: $B = -4.38$; $p < 0.001$; $d = -1.33$), and significant pre-post per session changes in anxiety, depression, difficulties in emotion regulation, several aspects of mindfulness, and interoceptive awareness. MBI+VR participants were significantly more adherent to treatment ($p = 0.020$
Seabrook et al. (2020) (Australia)	Community adult sample; $n = 37$; 64.9% female; Mean age = 37.86 ($SD = 14.56$)	Immersive: Oculus Go head mounted display headset	VR mindfulness app with 15-min program of guided, focused-attention mindfulness using a voice over within a virtual environment created from 360-degree video footage of a forest	Aimed to explore how VR can support mindfulness practice and to understand user experience challenges that may affect VR-supported mindfulness acceptability and efficacy	Mixed-methods; non-controlled; pre-post	State Mindfulness Scale (SMS); emotional state (drawn from circumplex model of emotion); Simulator Sickness Questionnaire (SSQ); Presence Questionnaire (PQ); semi-structured interview	State mindfulness ($p < 0.001$; $d = 1.80$) and positive affect ($p = 0.006$; $r = 0.45$) significantly increased after VR-mindfulness use. No significant changes in negative emotion, subjective arousal, or simulator sickness. The experience was described as relaxing, calming, and peaceful
Tong et al. (2015) (Canada)	Participants diagnosed with chronic pain; $n = 13$; 53.8% female; age range 35–55 ($m = 49$; $SD = 8.2$)	Immersive: Stereoscopic VR display mounted on movable arm for flexibility and patient comfort. Galvanic skin Response (GSR) sensors placed on patient fingertips	Virtual Meditative Walk (VMW) system encompassing a virtual environment paired with scenes of nature (e.g., forests) and linked to biofeedback for MBSR meditation training. (e.g., foggy forest becomes clearer based on biofeedback signalling reduced patient pain levels)	Tested minimal effectiveness of VMW combined with mindfulness-based stress reduction training and biofeedback helps chronic pain patients manage their pain	Two-arm RCT; within-between subjects; pre-post	GSR sensors; Numerical Rating Scale	VMW helped patients to manage chronic pain with real-time immersive visual signals and sonic feedback, corresponding to physio logical biofeedback data and decreased pain levels post intervention ($F(1, 11) = 8.16$, $p < 0.05$)

natural age-related changes, and experiencing elevated levels of regret, rumination, and negative affect (Baltes & Smith, 2003; Laidlaw et al., 2003; Casey, 2012). Conscientious development of gerontechnology interventions is once again crucial here. If done well, technological interventions targeting and developed in partnership with older adults may increase both general levels of compassionate service delivery, as well as users' self-compassion levels (Fozard, 2012; Schmitter-Edgecombe et al., 2013). Teaching self-compassion in a setting that facilitates easier practice, such as VR, could be beneficial for the adoption of attitudes of kindness towards oneself and the effects of aging.

Self-compassion interventions

Self-compassion interventions, or compassion-based interventions (CBIs), can be described as interventions that focus on cultivating compassion towards self and others through psycho-education, training and promotion of practices that enhance compassion (Kirby, 2017). CBIs have been linked to a variety of improvements in psychological health outcomes. Research has found CBIs to be effective at decreasing stress, anxiety, and depression (Kirby et al., 2017), and increasing compassion and empathy (Brito et al., 2018). A meta-analysis by Kirby and others (2017) investigated 21 RCT studies of CBIs and found significant short-term moderate effect sizes for life satisfaction, happiness, and decreased anxiety and depression. Additionally, small-to-moderate effects were found for psychological distress. However, a need for increased rigor in study design, as well as reporting, was identified for future studies of CBIs. Ferrari et al. (2019) conducted a more recent meta-analysis of 27 RCTs regarding the effects of CBIs on psychosocial outcomes and found large effects for rumination and eating behavior, and moderate effects for depression, anxiety, stress, self-criticism, mindfulness and self-compassion. Despite these promising findings, study inclusion criteria were based on a specifically western-lens following Neff's (2003) model of self-compassion. Future research assessing the efficacy of CBIs based on different models of self-compassion is needed given the debates over its conceptualization and operationalization (Khoury, 2019).

Furthermore, large-scale meta-analyses have linked the construct of self-compassion to enhanced well-being and reduced psychopathology in adults and adolescents (MacBeth & Gumley, 2012; Zessin et al., 2015; Marsh et al., 2018). Additionally, self-compassion shows potential for promoting resilience in the face of significant life stressors such as chronic health issues (e.g., Brion et al., 2014), divorce (e.g., Sbarra et al., 2012), parenting a child with a developmental disorder (e.g., Wong et al., 2016), and combat (e.g., Hiraoka et al., 2015). Notably, in two cross-sectional studies by Allen and others (2012) of adults aged 67–90 years old, self-compassion was found to positively moderate the relationship between physical health and psychological well-being. This moderating effect was particularly strong for older adults in poorer health, indicating that self-compassion may be especially useful for improved quality of life in aging populations with health challenges and could be a crucial component of successful aging (Rowe & Kahn, 1987; Allen et al., 2012; Rowe & Kahn, 2015). In a systematic review and meta-analysis of 11 studies by Brown and others (2019) of the effects of self-compassion on the older adult aging process, it was found that self-compassion was associated with decreased symptoms of depression and anxiety and increased psychological well-being. Meta-analytic findings indicated that self-compassion moderated the relationship between health problems and well-being (Brown et al., 2019), corroborating the findings of Allen et al. (2012). Overall, Brown et al. (2019) concluded that self-compassion is a promising resilience promoter for older adults. However, their search did not include qualitative studies, conference abstracts, or materials that were not published in English, limiting the breadth and depth of their findings, as well as the generalizability. Tavares and others (2020) conducted a scoping review of the self-compassion research base as it relates to psychological well-being of the older adult population. There were no restrictions on study design, or setting, so long as research was conducted with adults aged 60 or older, or with a mean age of 65 or older, and measured self-compassion and psychological adjustment (e.g., life satisfaction, depression or anxiety symptoms). Their review resulted in 12 studies, 1 qualitative and 11 mixed-methods design and found that self-compassion appears to be a valuable resource for older adult psychological adjustment and may promote resilience connected to age related challenges. All studies analyzed were cross-sectional therefore limiting the ability to draw meaningful conclusions from their findings. Another notable weakness of this review was the authors choice to exclude studies with compassion towards others as an outcome. This could limit the validity of the review's findings, given the considerable theoretical overlap between compassion directed to the self (self-compassion) and compassion directed towards others (compassion).

CBIs for older adults

Despite the findings from exploratory data and reviews linking the construct of self-compassion to improved well-being in older adults, there appear to be very few published studies examining the effects of CBIs on an exclusively older adult population. To this end, only one study was found when performing the literature search for this review. Perez-Blasco et al. (2016) examines the effects of a mixed mindfulness and compassion intervention for stress management in 45 healthy, community-based older adults aged 60 or older. Participants were randomly assigned to either the mindfulness-compassion intervention group or to a treatment as usual (TAU) control group. Each intervention session was 120 min long and there were 10 sessions in total. Findings suggest the synergistic benefits of combining mindfulness with self-compassion in interventions for older adults as compared to TAU. Study limitations include the small sample size and lack of follow-up data collection, restricting the ability to verify whether these are lasting improvements. As well, all participants were healthy, non-clinical older adults; therefore, it is unclear whether these findings would hold in older adults with health challenges such as cognitive decline. Further research in this area is clearly warranted given the potentially significant benefits for the aging process of older adults.

CBIs using VR

The research base of studies investigating VR-based CBIs is currently at a rudimentary stage. Findings from this review revealed six completed studies using VR to train self-compassion (Falconer et al., 2014; Holden, 2015; Falconer et al., 2016; Cebolla et al., 2019; Brown et al., 2020; Modrego-Alarcón et al., 2021) with an additional three protocol studies in existence (Baghaei et al., 2019; Baghaei et al., 2020; Baghaei et al., 2021). Perhaps the most influential study examining VR-based compassion training was conducted by Falconer et al., 2016. Designed based on the concept of virtual embodiment, this experimental study investigated an 8-min scenario where 15 participants with diagnosed depression practiced delivering compassion in one virtual body and then receiving it from themselves in a different virtual body (Falconer et al., 2016). The authors reported significant improvements in self-compassion and significant decreases in depression and self-criticism as a result of the experiment. Study limitations include the small number of participants, lack of control condition, repetition of one immersive VR scenario and a predominantly white, westernized sample. This study has led to further experimental studies investigating similar design paradigms to that of Falconer et al., 2016. In a recently published RCT by Modrego-Alarcón et al. (2021), the effects of a combined mindfulness and compassion intervention using VR were investigated in 280 university students. Students were assigned to one of three groups: "Mindfulness-based Programme" (MBP); "MBP + VR"; or "Relaxation." The MBP focused on two central components: mindfulness and self-compassion. Sessions were 90-min in length and were held in groups at a frequency of once per week for 6 weeks. It was found that both MBP and MBP+VR were superior to Relaxation for reducing stress, with medium-to-large effects found at post and follow-up. Notably, treatment adherence (i.e., retention rates and class session attendance) was significantly higher in the MBP+VR group, building support for the hypothesis that VR could be particularly effective at reducing attrition in MBIs and interventions in general (Slater et al., 1994; Navarro-Haro et al., 2017). Similar to Perez-Blasco et al., 2016, this study highlights the additive potential of combining MBIs and CBIs for improving well-being outcomes. Some limitations in this study include that previous familiarity with mindfulness and compassion was not assessed, nor was frequency of home practice during the intervention. Additionally, some analyses were underpowered. Finally, this study used an exclusively university student sample, making its findings difficult to generalize. Despite methodological weaknesses, findings for CBIs using VR appear to be promising; however, consistent with the level of existing research for *in vivo* CBIs for older adults, no studies investigating the effects of VR-based compassion training for older adults appear to have been published, to-date. Findings from VR-based CBI studies are summarized in Table 4 according to reference, sample, VR technology, VR environment, aims, design, measures, and results.

Discussion

Given the rapid aging of the global population, there is an increased need for effective and preventative health interventions in an age group that already has the highest rate of healthcare requirements and costs (GC, 2014; UN DESA, 2014; WHO, 2017). It is especially important to increase support for the significant portion of older adults experiencing mental and cognitive health conditions (Karel et al., 2012), due to their higher rates of comorbid physical and mental health conditions (Bartels et al., 2003; Gum et al., 2009; IOM, 2012) and the lower rate of mental health service access found among geriatric populations (Klap et al., 2003; Wang et al., 2005; Karlin et al., 2008; Bogner et al., 2009; MHF, 2018). To enhance the likelihood of successful aging, interventions should focus on pathways to increasing cognitive, physical, and psychological functioning, and decreasing disease-related disability through emphasizing active involvement and interest in life (Rowe & Kahn, 1997), while also accounting for cultural differences, chronic health issues, and socio-economic status barriers that may decrease the efficacy of certain interventions designed for WEIRD populations (Martinson & Berridge, 2015; Rowe & Kahn, 2015).

Implications for research

Growing evidence supports the importance of gerontechnology as an essential determinant to healthy aging and quality of life of older adults (Bouma et al., 2009). Gerontechnology has the potential to facilitate older adults' active participation in the healthy aging process and may benefit communication, health, mobility, work, housing, recreation, and self-fulfillment (Fozard et al., 2000). However, for its effective uptake, older adults need to perceive gerontechnology to be useful, as well as easy to use (Davis, 1989; Zhou et al., 2020). Therefore, technological solutions need to bridge the generational gap of technology use, instead of widening it. Additionally, further emphasis is needed on the research and development of gerontechnology for mental health, given the bias toward physical health-related technological support. Effective technological interventions for older adults should account for challenges and barriers commonly expressed by older adults and should be designed for easy use, increased social contact, fit with daily routines, and include access to straightforward, regular interactions with health providers, if needed (Jimison et al., 2008; Kang et al., 2010; Seifert et al., 2019). Despite its relatively recent introduction to the mainstream market, VR has the potential to be readily accepted by older adults due to its benefits compared to conventional treatments, such as accessibility, functionality, patient interaction with therapeutic stimuli, quicker positive health impacts, and safety conditions (Cherniack, 2011; Mohr et al., 2013; Robert et al., 2016; Benham et al., 2019; Montana et al., 2020). VR shows promise as a gerontechnology intervention; however, high quality empirical literature is currently limited and further research of its applications, feasibility and efficacy is needed. Additionally, component analyses of the mechanisms through which VR may improve well-being, as well as specific design elements that facilitate better outcomes, are important for clarification of the evidence-base and for the creation of optimally effective interventions.

Taken together, the research base is extremely sparse and sometimes non-existent with respect to VR-based nature interventions, MBIs, or CBIs for older adults, and is even more narrow in the area of older adult mental health and well-being. For instance, based on findings from this review, no study to-date has investigated MBIs or CBIs using VR for older adults and the studies examining nature-based VRs are very few and often methodologically weak. Of the research available, VR for older adults demonstrates potential as an intervention to enhance well-being, but there are significant methodological flaws that must be addressed in order to clarify the evidence base and create effective interventions (e.g., Dermody et al., 2020; Yen & Chiu, 2021). In general populations, nature-based, mindfulness and compassion VR interventions show promise for effectiveness at improving mental health and well-being outcomes (e.g., Falconer et al., 2016; Jerdan et al., 2018; Chandrasiri et al., 2020; Modrego-Alarcón et al., 2021). Currently, no study has investigated a VR-based combined mindfulness-compassion intervention incorporating natural settings for older adults. Given the pathways through which nature, mindfulness, and compassion interventions operate, it is likely that combining these interventions using VR could lead to improved resilience and well-being outcomes, such as mood and quality-of-life, and decreased symptoms of psychopathology. Additionally, a combined nature-mindfulness-compassion program based in VR could further enhance adherence and acceptability of mental health interventions for older adults, given preliminary findings indicating that VR: *1*) appears to be an effective method for improving mindfulness, compassion, and nature-based intervention adherence, and *2*) shows acceptability for older adults when administered under the right conditions (Zhou et al., 2020). Therefore, there is a need for studies with robust designs explicitly investigating nature interventions, MBIs, and CBIs for older adults, as well as interventions combining these three approaches, in addition to interventions integrating these approaches using VR technology, given their potential to improve quality-of-life and quality-of-care in soon to be the largest proportion of the population. Due to the prospective benefits, further clarification is warranted regarding the mechanisms contributing to the efficacy of VR-based nature interventions, MBIs and CBIs. Additionally, large-scale studies employing rigorous longitudinal RCT designs in cross-cultural and clinical populations are needed to better understand the effectiveness of VR interventions compared to non-VR interventions for mental health and well-being.

Implications for practice

Despite the evidence base for older adults still requiring further development, nature, mindfulness, compassion, and VR-based interventions all have support for general population mental health and well-being, in both clinical and non-clinical populations. Key implications for practice with geriatric populations include facilitating access to effective and engaging mental health interventions by clarifying the efficacy of VR-based psychological interventions for older adults, as robust research will be instrumental for effective preventative mental health care for a population in need of this type of programming. Additionally, collecting information on the feasibility, acceptability, and effectiveness of VR for older adults will deliver vital information regarding users' needs in the burgeoning field of digital therapeutics. Current evidence suggests that both nature-based interventions and MBIs improve emotional well-being and physical health among nonclinical community-dwelling samples of older adults. There is currently not enough research examining the efficacy of CBIs for older adults, but research examining positive associations between self-compassion as a construct and mental health outcomes suggests potential utility for CBIs in geriatric populations. Clearly, further empirical intervention studies are needed in this area. Additionally, mental health support programs that combine nature, mindfulness and compassion show promise given the connections between these constructs and their additive effects on psychological well-being in various older adult populations. Furthermore, despite the early stages of the research base, VR-based interventions appear to be a feasible and effective type of gerontechnology for both physical and psychological outcomes. Limitations to VR access should not be forgotten, there are currently technological, physical, and financial barriers,

TABLE 4 Examples of empirical studies of compassion-based VR interventions for mental health and well-being.

Author, year (Country)	Participants	Virtual technology	Virtual environment	Study aims	Study design	Study measures	Results
Brown et al. (2020) - Study 1 (United Kingdom)	Community sample with elevated levels of paranoia; n = 100; 37.0% female; age range 18–55 (M = 29)	Immersive: HTC Vive PRO head-mounted display	Two 3-min scenarios of an underground subway ride and an elevator - chosen to be potentially challenging for individuals with high-levels of paranoia. Self-compassion imagery techniques practiced between VR sessions	Investigated whether participants with high levels of paranoia who engaged in compassion training would experience increases in self-compassion and decreases in paranoid ideation when using VR, compared to controls	Two-arm RCT; between group; multiple time point	Green Paranoid Thoughts Scale-Part B (GPTS-B); State measure of paranoia post-VR- Visual Analogue Scale; State measure of self-compassion - Visual Analogue Scale	Self-compassion levels significantly increased (group difference = 2.12, C.I. = 1.57; 2.67, p = <0.001, d = 1.4), and paranoia levels significantly decreased (group difference = −1.73, C.I. = −2.48; −0.98, p = <0.001, d = 0.8), in the experimental group compared to the control group
Brown et al. (2020) - Study 2 (United Kingdom)	Community sample with elevated levels of paranoia; n = 100; 41.0% female; age range 18–55 (M = 29)	Immersive: HTC Vive PRO with Head-Mounted Display	Two 3-min scenarios of an underground subway ride and an elevator - chosen to be potentially challenging for individuals with high-levels of paranoia. Compassion-towards-others imagery techniques practiced between VR sessions	Investigated whether participants with high levels of paranoia who engaged in compassion training would experience increases in compassion for others and decreases in paranoid ideation when using VR, compared to controls	Two-arm RCT; between group; multiple time point	Green Paranoid Thoughts Scale-Part B (GPTS-B); State measure of paranoia post-VR- Visual Analogue Scale; State measure of compassion for others - Visual Analogue Scale; State measure of positive affect - Visual Analogue Scale	Levels of compassion for others significantly increased (group difference = 3.26, C.I. = 2.72; 3.80, p = <0.001, d = 1.7), and paranoia levels significantly decreased (group difference = −1.70, C.I. = −2.50; −0.89, p = <0.001, d = 0.8), in the experimental group compared to the control group
Cebolla et al. (2019) (Spain)	University students; n = 16; 75.0% female; age range 21–59 (M = 30.56; SD = 10.86)	Immersive: Oculus Rift VR Headset with Head-Mounted Display	Used The Machine To Be Another (TMTBA) as a body swapping system that uses multi-sensory stimulation to address relationship between identity and empathy. TMTBA allows users to see themselves in the body of another person connected through VR headsets	Analyzed effects of self-compassion meditation *via* VR (TMBTA-VR), compared to usual audio-only practice (CAU) and investigated whether imagery moderated effect of condition on adherence to meditation practice	Two-arm RCT; within-between-group; pre-post-follow-up	Patient-Health Questionnaire-9 (PHQ-9); Generalized Anxiety Disorder Questionnaire-7 (GAD-7); Betts' Questionnaire upon Mental Imagery (Betts' QMI); Positive and Negative Affect Schedule (PANAS); State Mindfulness Scale (SMS); Self-Other Four Immeasurable Scale (SOFI); Mindfulness Self-Care (MSCS); Adherence-to-practice - researcher designed question; Embodiment in TMTBA Questionnaire - adaptation of Rubber Hand Illusion Questionnaire	Significant main effects of time were found for the TMTBA-VR condition in positive qualities towards self (F(1,14) = 21.30, p < 0.001, η_p^2 = 0.60), positive qualities towards others (F(1,14) = 9.41, p = 0.008, η_p^2 = 0.40), decreased negative qualities towards self (F(1,14) = 5.40, p = 0.036, η_p^2 = 0.28), increased awareness/attention to mental events (F(1,14) = 25.66, p < 0.001, η_p^2 = 0.65) and bodily sensations (F(1,14) = 14.44, p = 0.002, η_p^2 = 0.51). TMBTA-VR showed similar frequen cies of compassion-practice adherence as CAU. Imagery ability was found to moderate the efficacy of the compassion VR condition (vs. control) at increasing adherence (F(1,12) = 5.95, p = 0.031)
Falconer et al. (2016) (United Kingdom)	Participants diagnosed with Major Depressive Disorder; n = 15; 66.7% female; age range 23–61 (M = 32.0)	Immersive: Oculus Rift VR headset with Head Mounted Display. Head tracked using 6-DOF Intersense IS-900. Body tracked using Natural Point Optitrack system.	Two VR phases. Phase 1 - participants interacted compassionately with a crying child avatar seated in front of them while embodied in an adult avatar. Phase 2 -	Investigated whether VR could be viable alternative to imagery-based approaches at enhancing experience of positive self-relating and self-compassion	Uncontrolled case series; multiple-time point	Patient-Health Questionnaire-9 (PHQ-9); Zung Self-Rating Depression Scale (SDS); Self-Compassion and Self-Criticism Scale (SCCS); Fears of Compassion Scales (FCS); Virtual Reality	Significant decreases in depression severity (F(1,12) = 14.04, p = 0.003, η_p^2 = 0.54) and self-criticism (F(1,12) = 23.41, p < 0.001, η_p^2 = 0.66) and significant increases in self-compassion (F(1,12) = 6.65, p = 0.02, η_p^2 = 0.36)

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TABLE 4 (*Continued*) Examples of empirical studies of compassion-based VR interventions for mental health and well-being.

Author, year (Country)	Participants	Virtual technology	Virtual environment	Study aims	Study design	Study measures	Results
		Virtual environment implemented with Unity 3D 4 game engine	participants embodied the child avatar and re-experienced their compassionate response from this embodied perspective	with individuals with MDD.		Experience Questionnaire - researcher designed questionnaire	
Falconer et al. (2014) (United Kingdom)	Female university student sample with high levels of self-criticism; First-Person Perspective (1PP) group: n = 22; 100% female; Mean age = 22 (SD = 5.1). Third-Person Perspective (3PP) group: n = 21; 100% female; Mean age = 22 (SD = 3.7)	Immersive: Oculus Rift VR headset with Head Mounted Display. Head tracked using 6-DOF Intersense IS-900. Body tracked using Natural Point Optitrack system. Virtual environment implemented with Unity 3D 4 game engine	Two VR phases. Phase 1 - participants interacted compassionately with a crying child avatar seated in front of them while embodied in an adult avatar. Phase 2 - participants embodied the child avatar and re-experienced their compassionate response from this embodied perspective	Investigated whether VR could be viable alternative to imagery-based approaches at enhancing experience of positive self-relating and self-compassion using and comparing an 1PP approach and a 3PP approach with highly self-critical female university students	Controlled study; between-groups; pre-post	Forms of Self-Criticizing/Attacking & Self-Reassuring Scale (FSCRS); Self-Compassion and Self-Criticism Scale (SCCS); International Positive and Negative Affect Schedule, Short Form (I-PANAS-SF); Two Forms of Positive Affect Scale (TFPAS); Virtual Reality Experience Questionnaire - researcher designed questionnaire	Observation and practice of compassionate response reduced self-criticism levels ($F(1,41) = 42.1$, $p < 0.001$, $\eta_p^2 = 0.51$). Experience of embodiment increased self-compassion ($F(1,41) = 15.87$, $p < 0.001$, $\eta_p^2 = 0.28$) and feelings of safety ($F(1,41) = 5.45$, $p = 0.025$, $\eta_p^2 = 0.12$)
Holden (2015) (United Kingdom)	University student sample with high-levels of self-criticism; n = 40; 50% female; age range 18–50	Immersive: nVisor SX111 Head-Mounted Display. Head position tracked *via* 6-DOF Intersense IS-900. Body tracked using Natural Point black body suit. Virtual environment implemented with Unity 3D 4 game engine	Virtual environment designed to accurately mimic the layout, content, and dimensions of VR lab where study was conducted. A large virtual mirror was added to the room. An adult and a child avatar were used in each compassion scenario with gender matched to participants	Aimed to clarify whether immersive VR compassion situation is more effective at improving levels of self-compassion, shame, self-criticism, and mood compared to a mental-imagery exercise (MI) in healthy participants with high-levels of self-criticism	Two-arm RCT; within-between group; pre-post-follow-up	Self-Compassion Scale (SCS); Forms of Self-Criticizing/Attacking & Self-Reassuring Scale (FSCRS); Test of Self-Conscious Affect-3 (TOSCA-3); Experience of Shame Scale (ESS); State Self-Compassion and Self-Criticism Scale (SSCC); State Shame and Guilt Scale (SSGS); International Positive and Negative Affect Scale-Short-Form (I-PANAS-SF); Imagery vividness - researcher designed questionnaire; Ease of recall - researcher designed questionnaire; Frequency of recall - researcher designed questionnaire	Small-to-medium effects on self-compassion ($F(2, 68.74) = 12.44$, $p < 0.001$) and shame ($F(2, 69.01) = 7.45$, $p = 0.001$) in both conditions post-intervention and at follow-up. Large effect on self-criticism ($F(2, 68.66) = 19.41$, $p < 0.001$) post-intervention and at follow-up. No differences found between conditions
Modrego-Alarcón et al. (2021) (Spain)	University students; n = 280; 78.9% female; Mean age = 22.25 (SD = 5.74)	Immersive: Samsung GearVR goggles	Series of mindfulness-or compassion-based exercises using different virtual environments paired to the activity and guided by audio instructions (e.g., three Good Things exercise with three aspects represented by geometric figures in landscape)	Tested efficacy of VR-based mindfulness-compassion programs in the Spanish university context at reducing stress levels	Three-arm RCT; between group; pre-post-6 months follow-up	Perceived Stress Scale (PSS); State-Trait Anxiety Inventory (STAI); Positive and Negative Affect Schedule (PANAS); Utrecht Work Engagement Survey Scale-Students (UWES-S); Maslach Burnout Inventory-Student Survey (MBI-SS); Emotion Regulation Questionnaire (ERQ); Five-Facet Mindfulness Questionnaire (FFMQ); Self-Compassion Scale (SCS)	VR mindfulness ($B = -2.77$, $d = -0.72$, $p = 0.006$) and conventional mindfulness ($B = -2.44$, $d = -0.59$, $p = 0.014$) were more effective than the relaxation condition at improving stress, as well as many of the secondary outcomes. Long-term effects of mindfulness training were mediated by mindfulness ($ab = -1.09$, 95% CI [−2.20 to −0.24]) and self-compassion ($ab = -1.14$, 95% CI [−2.45 to −0.09]). Treatment adherence was highest in the VR mindfulness group (Fisher $p < 0.001$)

and a dearth of research examining these specific barriers in VR design and studies. Additionally, given the research focus on WEIRD populations, it is unclear to what extent VR intervention efficacy could be globally generalized. Continuing to find ways to incorporate gerontechnology that promote acceptability amongst older adults is key in order for these interventions to have ecological validity. Whenever possible, gerontechnology interventions should be developed with the input of older adults and specifically targeted to their needs.

Conclusion

In summary, this review has evaluated the strengths, limitations, and potential of VR as a gerontechnology that enhances mental health and well-being. Research examining VR-based interventions that incorporate elements of nature, mindfulness, and compassion has major scholarly, technological and health implications. In particular, clinical interventions in this area have the potential to provide older adults with alternative, accessible, engaging, and safe care options. However, the current state of the field highlights the need for rigorously designed, applied studies that investigate the use of VR-based mindfulness, compassion and nature programs for older adult mental health and well-being. This is especially important given the increasing necessity for attention to the mental health needs of the older adult population, who will soon make up the majority of the global population.

Author contributions

All authors listed have made direct, substantial, and intellectual contribution to the work, and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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