1. Introduction

Accumulated evidence since the 1980s has demonstrated the restorative, stress-ameliorating effects of nature environments (Bratman, Hamilton, & Daily, 2012; Hartig, Mitchell, De Vries, & Frumkin, 2014; Menardo, Brondino, Hall, & Pasini, 2019; Mygind et al., 2019; Twohig-Bennett & Jones, 2015). As urban populations are predicted to nearly double between 2000 and 2030 (Seto, Güneralp, & Hutyra, 2012), and urban areas are forecast to triple between 2000 and 2030 (Desa, 2014), we can expect a growing demand for nature-based preventive health care and therapeutic solutions in the future. In the current era of rapid technological advancement, virtual natural environments are also one potential solution. Earlier research has shown that similar restorative effects have been produced with virtual environments and real natural environments (Browning, Shipley, et al., 2020; Naylor, Ridout, & Campbell, 2020; Roche, Liu, & Siegel, 2019; Stone, Small, Knight, Qian, & Shingari, 2014; White et al., 2018). While virtual environments are not a replacement for real nature, they could supplement nature contact, motivate people to experience nature outdoors (Yu, Lee, Lu, Huang, & Browning, 2020), and perhaps even increase environmental awareness and feelings of connectedness with nature (Litleskare, Machtnyre, & Calogiuri, 2020). In some environments, real-life nature contact is limited or impossible, such as in nursing homes or prisons. Furthermore, government actions such as COVID-19 lockdown policies in 2020 have restricted access to nature in many urban populations globally.

So far, hundreds of scholars and practitioners have used nature simulations in psychology research and clinical/therapeutic contexts (Browning, Saedi-Rizi, McAnirlin, Yoon, & Pei, 2020). We can expect that this trend will continue. The primary target audience of this work includes researchers and practitioners who want to understand the different forms of measures and modalities available for restorative nature simulations.

Timely reviews of past research on restorative virtual natural environments are scarce, with some exceptions (i.e., White et al., 2018; Browning, Saedi-Rizi, et al., 2020). We are not aware of any reviews that specifically have addressed two methodological questions in virtual natural environments: measures and modalities. With measures, in
this context, we refer mainly to **studied outcome variables**. According to a recent systematic review, the measured outcome is the most significant methodological issue in exploring simulated nature (Browning, Saeidi-Rizi, et al., 2020). Furthermore, measures may have an enormous impact on what direction restorative virtual natural environments are developed. For instance, are we aiming for stress-reduction or focusing on changing attitudes and behaviors to foster ecologically sustainable lifestyles?

Modalities, in this context, describe **virtual environments that utilize more than one mode of action**. The modalities can be sensory (i.e., visual, auditory, haptic, and olfactory), non-sensory (such as UV light or near-infrared radiation), or action-oriented (i.e., walking, breathing). While previously studied modalities have not been shown to have an overall effect on restoration (Browning, Saeidi-Rizi, et al., 2020), we feel that it is essential to further inquire why this may be so. It seems reasonable to assume that restoration occurs via multiple pathways (i.e., sensory, non-sensory, and action-oriented pathways) and that different modalities offer distinct means to access these restorative processes. Furthermore, action-oriented modalities could play a large role in user commitment.

To gain a deeper understanding of these subjects, we set out to perform an integrative narrative review (Cronin & George, 2020; Kudret, Erdogan, & Bauer, 2019; Souza, Silva, & Carvalho, 2010). We decided that this type of review would be the most suitable knowledge-synthesis vehicle for reviewing both theory and practice in the interdisciplinary field of restorative virtual natural environments. Research is scattered in many areas, including environmental psychology and cyberpsychology, human-computer interaction, engineering, physiology, medicine, and environmental science. The alternative approach to an integrative narrative review would have been a systematic review. However, we felt that focusing on the overall themes rather than the specific details is a better fit for synthesizing knowledge from this emerging field. Furthermore, we wanted to balance between discussing theoretical questions and empirical studies. The research field is scattered, and to our knowledge, there are no models or templates for guiding the selection of measures or modalities for restorative virtual natural environments.

We begin by providing a narrative review of restoration research’s theoretical background. The first goal (**Aim 1**) of this review is to define concepts, consider theoretical assumptions, and identify research gaps in current approaches regarding measures and modalities. We then perform a descriptive analysis to accomplish **Aim 2**: identify commonly investigated measures used to provide restoration and to accomplish **Aim 3**: identify the modalities used to provide restoration. The next component is to pursue **Aim 4**: introduce a novel conceptual framework constructed with a thematic analysis of the earlier empirical research and existing psychological theories. This “**Multidimensional Model of Restoration Measurement**” connects different restoration theory and measurement aspects. The conceptual framework is created from a cross-disciplinary psychological perspective but is hopefully helpful to readers approaching the topic from other backgrounds as well. The model’s purpose is to provide a template for researchers striving for comprehensive, contextually relevant measurement of restorative effects and future theory development. We conclude in pursuit of **Aim 5**: discuss the strengths and limitations of current theory and practice in restorative virtual reality environments and envision alternative future research themes. Fig. 1 below presents the aims of the study in a graphical form. The theoretical and empirical review occurred in parallel, after which we constructed a conceptual framework. Finally, the reviews and the conceptual framework formed a basis for discussing current theory and practice.

## 2. Restoration theory

### 2.1. Current understandings of restoration in natural environments

Restoration refers to the process of renewing, recovering, or re-establishing physical, psychological, and social resources or capabilities diminished in ongoing efforts to meet adaptive demands (Hartig, 2004). Several theories have tried to explain the mechanisms that make natural environments restorative. The most influential frameworks in explaining the effects include Kaplan’s (1995) attention restoration theory (ART), Ulrich’s and others’ (1991) stress reduction theory (SRT), the biophilia hypothesis (Kellert & Wilson, 1993), and prospect-refuge (Appleton, 1996, pp. 66–67) theories. To varying degrees, they can all be traced to the idea that humans have, through millions of years of evolution, adapted to living in certain types of environments and that current urban habitats are a mismatch to this. The biophilia hypothesis does not go much further than this, only stating that humans have an innate tendency to focus on life and lifelike processes. Attention restoration and stress reduction theory, on the other hand, make some additional propositions (for a more detailed explanation of ART and SRT, see Hartig, in press). In addition to these theories, Joye and Van den Berg’s (2011) processing fluency, or perceptual fluency account (PFA), conditioned restoration theory (Egner, Sütterlin, & Calogiuri, 2020), and Hartig’ in press relational restoration theory (RRT) and collective restoration theory (CRT) are more recent approaches to restoration.

In ART, attention is divided into voluntary and involuntary attention. Theoretically, a natural environment acts as a restorative mechanism for voluntary attention (Kaplan, 1995). A person can concentrate on a task only for a limited period at will, after which s/he may experience symptoms such as a loss of alertness and irritability. According to ART, a natural environment automatically attracts attention, which does not require attentional control. Thus, the processes used for voluntary

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**Fig. 1.** Study aims.
attention are not needed and have time to recover. Nature contact improves voluntary, executive attention from all the various aspects of attention, supporting the theory (Berman, Jonides, & Kaplan, 2008). In contrast, involuntary orienting attention or alerting attention have not been shown to improve after contact with nature. These areas of attention are distinguishable on both the behavioral and nervous system levels (Fan et al., 2002, 2005; Fan et al., 2005). According to SRT (Ulrich et al., 1991), natural environments suppress sympathetic nervous system activity and negative thoughts and thus stress. Stress is the process by which a person responds psychologically, and often with behaviors, to a situation that challenges or endangers well-being (Baum, Fleming, & Singer, 1985). SRT implies that certain types, suitably diverse habitats containing water or vegetation, are subconsciously preferred. Therefore, these environments attenuate the sympathetic stress response. For instance, research has shown that humans prefer savannah-like settings (i.e., Schebella, Weber, Schultz, & Weinstein, 2019), the environment for early human evolution, and there is also cross-cultural support for the findings (Falk & Balling, 2010).

Prospect-refuge theory (Appleton, 1996, pp. 66–67) states that people prefer landscapes that offer a clear view (prospect) and places to hide (refuge). There is some evidence that high prospect and low refuge environments are restorative, while low prospect high refuge environments could even increase stress and attention fatigue (Gatersleben & Andrews, 2013).

In their critique of evolutionary assumptions of restoration, Joyce and den Berg (2011) put forward a perceptual fluency account hypothesis of restoration. The supposition implies that information from natural environments is often processed more effectively than information from urban environments, leading to restorative effects. In particular, fractal characteristics of nature could be one reason for better processing fluency. The word fractal is a concept that can be simplified as a pattern where each part is self-similar, sharing the same mathematical character as the whole. There is preliminary support for the processing fluency hypothesis. Some studies have found that fractal art and architecture can have restorative effects measured by electrodermal activity and EEG (Hägerhäll et al., 2008; Taylor, 2006). However, we are unaware of a study that has successfully implemented these characteristics into a virtual environment.

Egger et al. (2017) have recently proposed a conditioned restoration theory. The theory builds on a classical conditioning paradigm, stating that positive affective responses are partly conditioned responses to natural environments. For instance, nature is often associated with leisure and play activities, leading to restorative conditioning.

Finally, Hartig, (in press) has recently proposed two theories that extend the conventional restoration narrative to the social dimension. These theories are coined relational restoration theory (RRT) and collective restoration theory (CRT). The theories build on the argument that restoration does not occur in a social vacuum. RRT proposes that a dyad or a small group’s social resources can be depleted. These resources can then be restored, for instance, by spending time together in nature. Similarly, CRT suggests that depletion and restoration of social resources can be collective. For instance, a simultaneous vacation period for a specific population could correlate with increased collective well-being for the duration of the leisure period. In contrast, cold summer weather could constrain collective restorative activities outdoors and have negative downstream effects on groups, such as increased stress and population-wide use of anti-depressants (Hartig, Catalano, & Ong, 2007).

2.2. Measures of restoration in natural environments

Regarding measurement, the chosen theoretical framework may implicitly direct how restoration is measured. If we use ART theory as our foundation, cognitive measurements such as attention (MacLeod, 1992), memory (Tulsky et al., 2014), reaction time (Robertson, 2007), creativity (Guilford, 1967), and brain physiology (i.e., EEG) receive the highest emphasis. Meanwhile, within a stress reduction framework, cardiorespiratory physiology would be emphasized. Heart rate variability (Shaffer & Ginsberg, 2017), heart rate, electrodermal activity (Dawson, Schell, & Filion, 2017), and blood pressure are some measures that come into thought when operating within a stress reduction framework. On the other hand, within the new conditioned restoration theory framework (2020), measuring affective responses would be emphasized. Some established questionnaires in this area include positive-negative affect scales (i.e., Curran, Andrykowski, & Studs, 1995; Watson & Clark, 1999) and questionnaires for discrete emotions (Harmon-Jones, Bastian, & Harmon Jones, 2016).

While existing theories imply that nature offers restorative benefits, the conventional theories in environmental psychology do not emphasize the importance of measuring connective aspects of restoration: social, ecological, or transcendent. For instance, how contact with nature can inspire people to act altruistically towards others (social), protect and restore the environment (ecological), or accept death as an inevitable transition in the life cycle (transcendent). One notable exception to presenting the collective dimensions is Hartig’s (in press) recent conceptualization of relational restoration theory (RRT) and collective restoration theory (CRT).

As Hartig, (in press) has already discussed the social dimension, we introduce the theoretical basis of the other two connective dimensions, ecological and transcendent. Ecological restoration is a concept that shares similarities in thought in the fields of ecopsychology (i.e., Roszak, Gomes, & Kanner, 1995; Norton, 2009; Plesa, 2019), and conservation psychology (i.e., Saunders, 2003; Clayton & Brook, 2005). Ecopsychologists emphasize that living in balance with nature includes a deep, reciprocal, psychological connection between humans and nature. Conservation psychologists, on the other hand, emphasize the importance of motivating people to act in more environmentally sustainable ways.

Transcendental restoration is a concept that exists in some form inside the field of transpersonal psychology (i.e., Hartelius, Caplan, & Rardin, 2007; Friedman & Hartelius, 2013). Among other topics, transpersonal psychologists focus on the study of psychological transformation and altered states of consciousness. Transpersonal experiences, such as revelations where the self and environment are perceived anew, are an important ingredient in studying human-nature connection; for instance, according to Kaplan and Talbot (1983), transpersonal qualities were the strongest reported theme among participants in a week-long wilderness trip study.

Including the connective dimensions of social, ecological, and transcendent in a restoration framework also receives support from motivational theories. Maslow’s hierarchy of needs (Koltko-Rivera, 2006; Maslow, 1969) implies that humans have different intrinsic motivations. Furthermore, Graves’ emergent cyclical theory of human development (Graves, 1970, 1974bib_Graves_1970bib_Graves_1974) states that humans have different motivational systems. The connective dimensions of restoration approximately correspond to the latter three needs/motivational systems in Maslow’s and Graves’ theories – belongingness/affiliation, self-actualization/existence, and self-transcendence/experience (Table 1). At present, the aspects are often overlooked in favor of more fundamental needs and motivations. This is a physical survival, lack of negative emotions, or a productive mind, which approximately correspond to the early three motivational systems in Maslow’s and Graves’ theories (Table 1). Summarizing this brief theoretical introduction, Table 1 attempts to link each type of restoration’s purpose to the different motivational systems and areas of psychology.

Social aspects of restoration represent the perceptions and actions of an individual towards other humans. Measuring social aspects of restoration could have implications for studying and designing virtual environments.
natural environments that promote social cohesion, empathy, and pro-social behavior. For instance, Seinfeld et al. (2018) found that virtual therapy can change domestic violence offenders’ perspectives by improving their ability to recognize fearful female faces. Additional studies showed that participants behaved altruistically in a trust game (Glennon & Barton, 2018) or felt more empathetic toward homeless people (Herrera, Ballesten, Weisz, Ogle, & Zaki, 2018) after exposure to a virtual natural environment. Potential ways to quantify social restoration include measuring empathy (Lawrence, Shaw, Baker, Baron-Cohen, & David, 2004), altruism (Rushton, Chrisjohn, & Fecken, 1981), prosocialness (Caprara, Steca, Zelli, & Capanna, 2005), and inclusion of the other in self (Aron, Aron, & Smollan, 1992).

Ecological aspects of restoration represent the perceptions and actions of an individual towards natural environments. Measuring ecological aspects of restoration has implications for both health and environmental sustainability. For instance, nature connectedness influences sustainable consumption behavior such as green purchasing, reusability, and recycling (Dong et al., 2020). As another example, the nature relatedness scale has been shown to correlate with environmental rankings, behavior, and frequency of time in nature (Nisbet, Zelenksi, & Murphy, 2009). There are many possible alternatives for measuring ecological aspects of restoration, including nature relatedness (Nisbet et al., 2009), general ecological behavior (Kaiser, 1998), pro-environmental behavior (Larson, Stedman, Cooper, & Decker, 2015), and the connectedness to nature (Mayer et al., 2004).

Transcendent aspects of restoration represent the perceptions and actions of an individual towards all of existence. Suppose social restoration implies improved human connection, and ecological restoration implies improved nature connection. In that case, transcendent restoration means improved connection with all of existence, even to the point of hypo-egoic (Leary, Adams, & Tate, 2006), complete loss of subjective self-identity. Virtual reality can immerse individuals into virtual environments that transcend the limitation of their physical self (i.e., Barberia, Oliva, Bourdin, & Slater, 2018), alter perspectives, and disrupt rigid patterns of experience (Aday, Davoli, & Bloesch, 2020). Further, natural environments can provide transcendent experiences (Williams & Harvey, 2001), making virtual natural environments particularly promising for this type of restoration. Transcendent experiences have previously been studied in the context of psychedelics (i.e., Griffiths, Richards, Johnson, McCann, & Jesse, 2008), sensory deprivation (Kjellgren, Sundequist, Sundholm, Norlander, & Archer, 2004), binaural beats (Curtis, 2007), and in some instances of simulated nature (Kjellgren & Buhrkall, 2011). Transcendent experiences are associated with positive health outcomes (i.e., Noble, 1987; Griffiths et al., 2008), as well as nature relatedness (Kettner, Gandy, Hajen, & Carhart-Harris, 2019), and inclusion of nature in the self (Gómez-Olmedo, Valor, & Carrero, 2020).

Possible ways to assess transcendent experiences in virtual environments include metrics that measure altered states of consciousness (i.e., Dittrich, 1998; Dittrich, Lamparter, & Maurer, 2010; Studerus, Gamma, & Vollenweider, 2010), religious involvement (Piedmont, Ciarrachi, Dy-Liacco, & Williams, 2009), and meditation frequency (Strait et al., 2020). The measures also involve concepts such as the daily spiritual experience (Underwood & Teresi, 2002) and the fear of death (i.e., Lester & Abdel-Khale, 2003; Florian & Kravetz, 1983).

### 2.3. Modalities of experiencing restoration in natural environments

The visual experience is the most studied aspect of nature experiences (Franco, Shanahan, & Fuller, 2017), and the benefits of nature are still generally examined through the visual signifiers of ‘green’ and ‘blue’ space (Bates, Hickman, Manchester, Prior, & Singer, 2020). Visual experience is also a definitive aspect of VR. Furthermore, the visual sense has the most information processing capacity (Zimmerman, 1989). However, many experiments demonstrate that restoration is not restricted to vision alone.

According to Hedblom, Gunnarsson, Iravanì, et al. (2019), olfactory stimuli may be more effective than visual stimuli for reducing electrodermal activity (EDA), a measure of sympathetic nervous system activity (bib.Dawson.et.al.2017). Furthermore, Song, Iikei, and Miyazaki (2019) showed that combined visual and olfactory stimuli exhibited a significantly decreased oxyhemoglobin concentration in the prefrontal cortices compared to visual only stimuli. Third, Annerstedt et al. (2013) showed that an audiovisual virtual environment only increased parasympathetic nervous system activity (HRV) when it included sounds of nature. Fourth, Ahmanieni, Lindholm, Muller, and Taipalus (2017) showed that an audio-only setting was more effective for lowering sympathetic nervous system activity (EDA) than the same environment with 360-degree videos. Fifth, Horichi et al. (2014) found that viewing and not viewing a real forest had the same effect on blood pressure and heart rate variability. As a side note, there also seems to be no reason to assume that visually impaired people, in the absence of visual stimuli, would have more difficulties achieving restorative states than persons with normal eyesight.

The studies cited above show that physiological restoration cannot be reduced to a visual phenomenon. While moving from the visual experience to a multi-sensory experience is a step forward, it leaves many issues hidden. Multiple non-sensory modalities could be helpful for restorative virtual environments. Non-visual pathways for restoration include ingestion or inhalation of phytoncides, negative air ions, and microbes (bib.Franco.et.al.2017). Additional pathways include certain frequencies of the electromagnetic spectrum. UV light provided by sunlight has substantial psychophysiological effects, including vitamin D synthesis, reduced blood pressure, and improved mood (Kalajian, Aldoukhi, Veronikis, Perrons, & Holick, 2017). As another example, near-infrared and infrared radiation (NIR and IR) wavelengths are employed in clinical and biohacking settings through photobiomodulation (PBM) devices. They are also naturally present in sunlight and have many possible health benefits, such as energy production at the cellular level, which may lead to increased feelings of vitality (i.e., Barolet, Christiaens, & Hamblin, 2016; Hamblin, 2018; Salehpour et al., 2019; Veto, 2020).
Examples such as these demonstrate that restoration theories are not integrated with fields such as biophysics and photomedicine. More interdisciplinary research could help advance restoration theory, such as how different electromagnetic frequencies affect physiological restoration in humans.

An additional issue with the focus on visual-oriented restorative environments is the overlooked opportunities of action-oriented modalities. According to ART, a natural environment automatically attracts attention, giving the processes used for voluntary attention time to recover. Similarly, SRT suggests that certain natural environments automatically suppress stress. These ideas may lead to the inaccurate conclusion that virtual natural settings could offer mostly passive restoration. Including activities in the environments may increase the restorative benefits of nature, as well as user commitment. For instance, meditation, breathing exercises, physical exercise, interactions with animals, and social interaction could all have synergistic benefits with restorative environments.

In sum, we emphasize that restoration is a phenomenon with multiple modalities and dimensions. Revealing hidden assumptions about restoration measurement and modalities can aid in transcending limits regarding the possibilities of virtual natural environments.

2.4. Defining restorative virtual natural environments

For this paper, we conceptualize virtual reality as telepresence (Steuer, 1992), a sense of being in an environment generated by technological means. Furthermore, we define virtual reality (VR) in the broader sense of extended reality (XR), similar to LaValle (2019). Putting the definitions for restoration, natural environment, and virtual reality together, we define restorative virtual natural environments as VR environments that aim to produce similar effects as restorative natural environments. Fig. 2 shows the conceptual relationships between VR, restorative VR, nature VR, and restorative virtual natural environments. For instance, an example of a restorative non-nature-based VR could be a biofeedback-assisted meditation application built in an abstract setting. An example of a nature VR that is not restorative could be a VR horror game with some natural elements.

3. Empirical studies on restorative virtual natural environments: measures and modalities

3.1. Methods

We performed a literature search to find empirical studies on virtual restoration between 2010 and 2020. As VR technology has evolved rapidly over the last decade, we selected a cutoff date of 2010 to omit studies with more outdated technology (LaValle, 2019). In practice, the studies utilized either head-mounted displays (HMDs) or immersive room spaces with large displays (i.e., cave audio-visual experience [CAVE], Cruz-Neira, Sandin, DeFanti, Kenyon, & Hart, 1992; Anthes, García-Hernández, Wiedemann, & Kranzlmüller, 2016). We excluded thesis/dissertation studies, and studies reported in other venues than scientific publications.

The search was an iterative process: we conducted search queries and consequently found new articles between January and December 2020. We started by searching Google Scholar and PubMed databases using keywords restorative, restoration, nature, natural, virtual environment, and virtual reality. For Google Scholar search, we used all of the keywords in the search query. For PubMed, we used the resulting eight combinations of:

- restorative OR restoration
- nature OR natural
- virtual environment OR virtual reality

Google Scholar returned approximately 17000 results, while PubMed returned 264 in total. Due to many results in Scholar, we only examined the most relevant search results during each iteration (250), similar to the number of studies returned by PubMed (264). We selected a study for further analysis if the abstract mentioned the utilization of nature content, virtual reality technology and measured at least one restorative outcome. The keyword searches resulted in 31 inclusions. In addition to the keyword search, we performed snowballing and backward snowballing searches (Badampudi, Wohlin, & Petersen, 2015) on the included articles. We also checked the references in review articles we found by the initial keyword search and snowballing. 11 additional items were found by snowballing and review article inclusion. After all iterations, we included 42 studies in the review.

3.2. Overview

29% of the studies were published in 2020, 33% in 2019, 21% in 2018, and 17% before 2018, indicating increased attention to the research topic. The number of participants in the studies varied from 4 to 154 (median 47.5). The restorative period’s reported duration ranged between 40 s and 60 min, with a median of 6.5 min. Thirty-nine of the studies utilized VR headsets, while three used a room space with a large display.

We found a relatively even distribution between the different publication fields. 33% of the studies were published in environmental science and natural science publications; 26% of the research in engineering, human-computer interaction, electronic health, and computer science. 22% of the studies were published in psychology venues. Finally, 19% of the studies were published in medicine, physiology, and health sciences publications. In 29% of the cases, the publication venue overlapped two of these research fields. See supplementary material (Table S1) for more details.

3.3. Measures

Table 2 on the following page describes the studies’ measures abstracted into six possible categories: (1) Physiological, (2) Affective, (3) Cognitive, (4) Ecological, (5) Social, and (6) Transcendent.

For instance, heart rate variability includes time (RMSSD/SDNN) and frequency domain (LF/HF) measures, which are physiological measures on a higher abstraction level. Similarly, discretely measured emotions, such as disgust, fear, anxiety, interest, calmness, happiness, and joy, form the discrete emotions category, which are affective measures on a higher abstraction level. In some cases, a measured outcome could fit two different types (i.e., physiological and affective or cognitive). In these cases, we placed direct physiological measures in the physiology category and self-report measures in other categories.

43% of the measurements were physiological outcomes, 42% were affective outcomes, 10% were cognitive outcomes, and 5% were ecological outcomes. A single study reported one social variable
(Glennon & Barton, 2018). No studies reported transcendent outcome variables. Measures such as demographic information, previous experience with VR devices, and general feedback are omitted from the table.

3.4. Modalities

Table 3 below shows the different modalities used in the studies: visual input (panoramic photographs, 360 photos, 2D videos, 360 videos, and 3D), auditory input, olfactory input, haptic or thermal input, and action-oriented modalities. See also supplementary material (Table S2) for an overview incorporating both measures and modalities.

Concerning sensory modalities, all the studies used visual modality. For the visual sense, most of the studies used real imagery, either 360-degree videos (18 studies), 2D videos (Gerber et al., 2017), panoramic photographs (Gao et al., 2019), or 360-degree videos (Glennon & Barton, 2018; Hedblom et al., 2019a; Hedblom et al., 2019b). Two studies utilized both computer-generated imagery and 360-video (Nukarinen et al., 2020; Yeo et al., 2020). The remaining 17 studies used computer-generated imagery (3D). The environments varied from indoor biophilic environments (Yin et al., 2018), roadsides with greenery (Birenboim et al., 2019), and parks (Hedblom, Gunnarsson, Schaefer, et al., 2019) to beaches (Amores et al., 2018), national forests (Yu et al., 2018), and underwater environments (Soyka et al., 2016).

Twenty-eight (67%) of the studies also used the auditory modality. Most studies that included the auditory modality had nature sounds in the soundscapes. Singing birds (Hedblom, Gunnarsson, Schaefer, et al., 2019), campfire sounds (Blum et al., 2019), wind sounds (Prabhu et al., 2020), crashing waves (Gerber et al., 2019), waterfall sounds (Yu et al., 2020), and underwater sounds (Soyka et al., 2016) were mentioned. The one soundscape without nature sounds included music (Gerber et al., 2017); some studies also utilized music in addition to nature sounds (Ahmaniemi et al., 2017; Anderson et al., 2017; Blum et al., 2019; Rockstroh et al., 2019; Serrano et al., 2016). One study used an auditory attention task during the restoration period (Chung et al., 2018).

Five studies (Amores et al., 2018; Hedblom, Gunnarsson, Iravani, et al., 2019; Schebella et al., 2019; Serrano et al., 2016; Valtchanov et al., 2010) used some form of olfactory stimuli. Valtchanov et al. (2010) used a “forest breeze” air freshener as the olfactory modality, while Serrano et al. (2016) used a ceramic oil diffuser with a lavender scent. Two studies used computer-controlled scent displays with lavender (Amores et al., 2018), grass, and fir scents (Hedblom, Gunnarsson, Iravani, et al., 2019). One study utilized cotton pads with grass, soil, leave, and flower scents attached to a head-mounted display (Schebella et al., 2019).

Finally, haptics, including tactile (Serrano et al., 2016; Valtchanov et al., 2010; Valtchanov et al., 2010) and thermal stimuli (Anderson et al., 2017), were used in three studies. For the haptic sense, Valtchanov et al. (2016) used a rumble platform to stimulate the haptic sense while walking. Serrano et al. (2016), on the other hand, used artificial grass that the users could touch in the virtual environment. In one study, thermal stimuli, in the form of a heat lamp, were used to present an artificial sun (Anderson et al., 2017).

Thirteen studies involved active modalities, including exploration (Serrano et al., 2016; Valtchanov et al., 2010), walking (Galguturi et al., 2019), cycling (Birenboim et al., 2019; Kim & Lee, 2018; Wang et al., 2020), and biofeedback-assisted breathing (Blum et al., 2019; Prabhu et al., 2020; Rockstroh et al., 2019; Soyka et al., 2016). One study used mindfulness meditation (Seabrook et al., 2020). Finally, Palanica et al. (2019) used an alternate use creative task, and Chung et al. (2018) used an auditory attention task inside the environments as part of the experimental procedures. The remaining 29 studies didn’t include action-oriented modalities; they can be described as free form relaxation.

4. Conceptual model

Based on the theoretical and empirical review, we performed a thematic analysis (Braun & Clarke, 2006; Clarke, Braun, & Hayfield, 2015, pp. 222–248), abstracting existing theories and measures to build a conceptual model to describe restoration measurement. The analysis roughly followed a recursive six-step process of familiarizing with the data (1), generating initial codes (2), searching for themes (3), reviewing the themes (4), naming and defining the themes (5), and reporting (6). The abstraction was an iterative process in which the aim was to connect theories and measurements using both top-down and bottom-up approaches.

Table 2

| Measure                      | Cognitive          | Ecological                  | Social                        | Transcendent                     |
|------------------------------|--------------------|------------------------------|-------------------------------|----------------------------------|
| Physiological                |                    |                              |                               |                                  |
| Heart rate (N = 19)          | Positive and negative affect (N = 18) | Attention (N = 5) | Perceived environmental features (N = 2) | Trust game (N = 1) |
| Electrodermal activity (N = 14) | Discrete emotions (N = 16) | Reaction time (N = 2) | Tendency to perceive natural beauty (N = 1) |                              |
| Heart rate variability (N = 13) | Presence, being present (N = 12) | Short-term memory (N = 2) | Attitudes towards wolves (N = 1) |                                  |
| Blood pressure (N = 9)       | Perceived restorativeness (N = 7) | Creativity (N = 2) | Commitment to environment (N = 1) |                                  |
| EGG (N = 4)                  | Perceived stress (N = 3) | Mindful attention awareness (N = 1) | Inclusion of nature in self (N = 1) |                                  |
| Cortisol (N = 2)             | Perceived pleasantness (N = 1) | Distraction (N = 1) | Biodiversity experience (N = 1) |                                  |
| Salivary amylase (N = 2)     | Qualitative experience (N = 1) | State mindfulness (N = 1) | Perceived plant and animal diversity (N = 1) |                                  |
| Respiratory rate (N = 2)     | Experience rating (N = 1) | Self-efficacy (N = 1) |                               |                                  |
| Walking speed (N = 1)        | Preference (N = 1) | Mind-wandering (N = 1) |                               |                                  |
| Fixation/saccade ratio (N = 1) | Motivation (N = 1) |                               |                               |                                  |
| Blood volume pulse (N = 1)   | Restorative quality (N = 1) |                               |                               |                                  |
|                              | Restoration outcome (N = 1) |                               |                               |                                  |
|                              | Feeling intensity (N = 1) |                               |                               |                                  |
|                              | Need for affect (N = 1) |                               |                               |                                  |
|                              | Exertion (N = 1) |                               |                               |                                  |
|                              | Pain (N = 1) |                               |                               |                                  |
| Total: 68                    | Total: 67          | Total: 16                    | Total: 8                      | Total: 1                         | Total: 0                       |
3.3: Measures). The process for analyzing measures involved fitting together high-level concepts and measures using sub-concepts. The chosen sub-concepts were influenced by the sympathetic-parasympathetic paradigm (Goldstein, 1987; Porges, 2010, p. 306), the broaden-and-build model of emotions (Fredrickson, 2004), Guilford’s concepts of convergent and divergent thinking (Guilford, 1957), as well as attitude-behavior consistency (Fazio & Zanna, 1981; Gross & Niman, 1975). Sub-concepts of physiology includes sympathetic and parasympathetic nervous system activity: the two sides of the physiological stress response (Goldstein, 1987; Porges, 2010, p. 306). For affect, the sub-concepts include positive and negative affect: broaden-and-build
(Fredrickson, 2004) orientation and survival-orientation. Cognition sub-concepts include convergent and divergent thinking (Guilford, 1957): focusing on an idea and generating new ideas. The connective sub-concepts are ecological perceptions and actions, social perceptions and actions, and transcendent perceptions and actions. This division highlights how perceptions and attitudes often differ from actions and behaviors, also known as the attitude-behavior consistency/inconsistency (Fazio & Zanna, 1981; Gross & Niman, 1975).

Table 5 visualizes the connections between each high-level concept, its sub-concepts, and specific example measures. The table highlights select measures for particular aspects of restoration. Rather than providing exact recommendations, the purpose was to present clear examples of measures that easily fit into one high-level category.

4.3. Multidimensional model of restoration measurement

Fig. 3 above presents the final model. Restoration theories are placed near the high-level concepts they are most related to. The three dimensions entirely inside the grey circle (physiological, affective, and cognitive) present individually oriented measures, while the outer three dimensions (ecological, social, and transcendent) present connection-oriented measures. The individually oriented measures are related to processes oriented to physiological and psychological survival, i.e., fighting-or-flighting vs. resting-and-digesting (Goldstein, 1987; Porges, 1957): focusing on an idea and generating new ideas. The connective measurements are more concerned with homeostatic needs, including survival, security, and competence.

| HIGH-LEVEL CONCEPT | SUB-CONCEPT | EXAMPLE MEASURE |
|--------------------|-------------|----------------|
| PHYSIOLOGICAL RESTORATION | Sympathetic Nervous System Activity | Electrodermal Activity (bib.Dawson.et.al 2017; Dawson et al., 2017), Heart Rate, Respiratory Rate |
| | Parasympathetic Nervous System Activity | Heart Rate Variability (Shaffer & Ginsberg, 2017), Heart Rate, Respiratory Rate |
| AFFECTIVE RESTORATION | Positive Affect | PANAS-X (Watson & Clark, 1999), POMS-SF (Carran et al., 1998), DEQ (Harmon-Jones, Bastian, & Harmon-Jones, 2016) |
| | Negative Affect | |
| COGNITIVE RESTORATION | Convergent Thinking | The Stroop Task (MacLeod, 1992), NIHTB-CB (Tulsky et al., 2014), SRTT (Roberson, 2007) |
| | Divergent Thinking | The Alternate Uses Task (Guilford, 1967) |
| SOCIAL RESTORATION | Social Perception | Inclusion of Other in the Self Scale (bib.Aron.et.al 1992Aron et al., 1992), The Empathy Quotient (Lawrence et al., 2004) |
| | Social Action | The Self-Report Altruism Scale (Rushton, 1981), Prosocial Scale (Caprara et al., 2005) |
| ECOLOGICAL RESTORATION | Ecological Perception | The Connectedness to Nature Scale (Mayer & Frantz, 2004), The Nature Relatedness Scale (Nisbett, 2009) |
| | Ecological Action | General Ecological Behavior Scale (Kaiser, 1998), Pro-Environmental Behavior Scale (Larson et al., 2015) |
| TRANSCENDENT RESTORATION | Transcendent Perception | OAV (bib.Studerus.et.al 2010Studerus et al., 2010), The Daily Spiritual Experience Scale (Underwood & Teresi, 2002) |
| | Transcendent Action | Religious Involvement Scale (Piedmont et al., 2009), Meditation Frequency (Strait et al., 2020) |

5. Discussion

This paper’s main contribution is to provide an integrative narrative review of current measures and modalities in the emerging field of restorative virtual natural environments (Aim 1, Aim 2, Aim 3). In addition to critiquing prevailing theoretical assumptions of restoration, we reviewed experimental research across diverse areas, including psychology, engineering, medicine, and environmental science. We then presented a multidimensional model of restoration measurement to integrate different theories and approaches related to restorative virtual natural environments. This examination concludes with insights into the questions related to research applications and the design of restorative virtual environments, particularly the possible measurements and modalities employed in research studies.

We will begin the discussion with some insights into current measurement practices in restorative VR. After this, we will discuss practical implications, future research needs, and the limitations in the field and of the review (Aim 5).

5.1. Measures

We found that physiology and affective measurements were well represented in the reviewed literature. Other aspects were underrepresented, however, including cognitive measures and divergent thinking. Some restoration measures were mostly or entirely missing in the reviewed studies, including social, ecological, and transcendent elements. However, these aspects were present in other related restoration and VR literature. For instance, empathy has been studied in social VR (Seinfeld et al., 2018) and pro-environmental behavior in the context of nature videos (Klein & Hilbig, 2018). Transcendent experiences have previously been investigated in sensory deprivation (Kjellgren et al., 2004), other VR applications (Barberia et al., 2018), and non-VR nature simulations (Kjellgren & Buhrkall, 2010).

One explanation of the uneven distribution of measures is that the less represented measurement categories typify value orientations that are higher in the hierarchy of needs, as described in Maslow’s theory (Kolstiko-Rivera, 2006; Maslow, 1969). Maslow’s theory suggests that as more basic human needs are satisfied, a new set of needs emerges, forming a hierarchy of needs. The first three measurement categories (physiological, affective, and cognitive) are more oriented towards basic homeostatic needs, including survival, security, and competence. Meanwhile, the connective measurements are more concerned with interacting with higher-order systems (i.e., humanity, the Earth, and the Universe), measuring the human needs for social affiliation, continuing existence of life on Earth, and experience in totality. Further research and review articles are needed to identify why measures are clustered around specific needs.

For future work, the multidimensional measurement could ensure that individuals with different value orientations and needs can report the aspects of restoration that are the most meaningful to them.
Furthermore, to measure the effects of novel technological applications, social, ecological, and transcendent measures of restoration are required. For instance, virtual natural environments could be used to facilitate empathy, learn resource-efficient use of natural resources, and provide peak experiences (McDonald, Wearing, & Ponting, 2009).

We noticed that a significant part of the present evidence is based on before-after treatment comparisons and comparisons to other virtual environments. When comparing before-after values following an acute stressor, time and spontaneous recovery may be the simplest explanation for the differences in outcomes. We consider that before-after comparisons are a helpful addition to an experimental procedure but only when coupled with a control condition. Using a non-nature-based VR experience as the control may limit ecological validity, however; restorative virtual environments will likely appear more advantageous if the comparison is made to synthetic environments lacking meaningful content rather than to real natural environments.

Some studies present other types of controls. Rockstroh et al. (2019) used nature videos, Yin et al. (2018) used actual potted plants, and Ahmaniemi et al. (2017) used an audio-only condition with headphones. Such controls present realistic situations of what is already available in most potential use cases without additional investments and could also be recommended for future studies. Outdoor environments, ranging from city parks to wilderness, also make for compelling comparisons when the purpose is to compare real and simulated nature directly. Of the studies reviewed here, Calogiuri et al. (2018) had a nature walk as a control. Other studies with outdoor conditions utilized seated rest (Browning, Minnaugh, et al., 2020; Chirico & Gaggioli, 2019; Nukarinen et al., 2020; Palanica et al., 2019).

Another issue that may hinder ecological validity is the lack of long-term studies in the actual use context. We did not find any long-term studies in our literature search. Long-term field studies with control groups for different target populations could confirm whether the restorative effects occur over the long-term and in real-life settings.

We presented the Multidimensional Model of Restoration Measurement to make it possible to consider different measurement aspects based on the target populations of interest to researchers and practitioners. On the one hand, to reduce pain and negative emotions in dental health care, physiological and affective measures could receive the highest emphasis. On the other hand, urban offices, emphasizing productivity, could be places for cognitive measures. In a prison context, social questionnaires could be used to study the effect of restorative VR on altruistic behavior among prisoners. In the educational context, VR experiences could emphasize ecological scales; children might internalize ecological attitudes and behaviors from restorative virtual environments. Finally, in clinical contexts with terminal care patients, transcendent measures could assess the impact of restorative VR on the

Fig. 3. Multidimensional model of restoration measurement.
fear of death.

While the context of use plays an essential role in selecting measures, we want to raise three additional issues related to further developing the measurement model and standardized measurement practices in particular. The first issue involves the control environment for standardization. For instance, recent research suggests that old-growth forests and mature commercial forests are more restorative than urban forests or young forests (Simkin, Ojala, & Tyrväinen, 2020). Findings on the restorative qualities of different natural environments can guide the decisions on what to use as comparison conditions for developing standardized measures for restorative virtual nature.

The second issue is the selection of standardized measures under one of the dimensions. For example, how comparable is the restorative experience that produces a 20% reduction in heart rate with one that results in a 5% change in electrodermal activity? One way to begin would be to study the associations between measures with correlative research, as done in other fields (i.e., Rastgoo, Nakisa, Rakotonirainy, Chandran, & Tjondronegoro, 2019). Measurements with high correlation could be redundant to include in the same use case, as the high correlation could imply that they measure the same underlying process. Meanwhile, other measures with smaller correlations could indicate different processes, warranting further investigation.

The third issue concerns the relevance of particular measurement dimensions for a standardized measurement kit. One way forward would be to focus on duration. For instance, only 30 min a week of nature exposure can decrease the prevalence of high blood pressure in a population by 9% (Shanahan et al., 2016). On the other hand, four days of immersion in a natural setting improved creative problem-solving performance by 50% (Atchley, Strayer, & Atchley, 2012). Each dimension of restoration may be tied to a specific time interval. An interesting hypothesis for further research would be that restoration types higher in the hierarchy of needs require a longer exposure duration.

5.2. Practical implications and future research needs

In addition to developing measurement practices, the possibilities of VR technologies could be better utilized. One option is to include contemplative activities in virtual environments to increase the user’s overall restorative benefits. Unlike more movement-oriented activities such as walking or cycling, these kinds of activities are also not as likely to induce cybersickness. Cybersickness rarely occurs when movement is limited (Browning, Shipley, et al., 2020), and movement is the presumptive driver of cybersickness (Howard & Van Zandt, 2021).

Potential contemplative activities include mindfulness (Khoury et al., 2013) and breathing (Pal & Velkumary, 2014) exercises, which can reduce stress and increase parasympathetic activity. Previous research also indicates that there is a synergy between mindfulness practices and a restorative environment. For instance, natural scenery may facilitate mindfulness practice (Lyneus, Lundgren, & Hartig, 2017), and open-monitoring meditation in a natural environment can enhance attention performance (Lyneus, Lindberg, & Hartig, 2018). Furthermore, one study included in the review (Seabrook et al., 2020) showed that meditating in nature VR increased state mindfulness.

Combining contemplative activities and biofeedback could also have synergistic benefits. VR systems could help the user to observe and regulate physiological functions, such as breathing, by measuring physiological data, such as HRV (bib.Blum.et.al.2019.Blum.et.al.2019) and EDA (Amores, Fuste, & Richer, 2019). Multiple studies included in the review utilized biofeedback-assisted breathing (bib.Blum.et.al.2019.Blum.et.al.2019; Prabhu et al., 2020; bib.Rockstroh.et.al.2019.rockstroh.et.al.2019; Prabhu et al., 2020). Among other benefits, these interventions can improve short-term HRV (bib.Rockstroh.et.al.2019.rockstroh.et.al.2019), reduce pain and anxiety (Prabhu et al., 2020), and enhance mental-wandering and help participants focus on the present moment (bib.Blum.et.al.2019.Blum.et.al.2019).

Studies on social VR show that VR can change people’s perspectives towards others (Herrera et al., 2018; Seinfeld et al., 2018). Furthermore, the possibilities are not limited to social perspective-taking. For example, in addition to viewing wild animals in VR (i.e., Filler et al., 2020), VR makes it possible for users to experience themselves as wild animals or any life-form. For instance, the ‘Inside Tumucumaque’ VR art installation (Inside Tumucumaque, 2019) allowed the users to "adapt the senses" of different animal species (such as a bird, bat, or a frog) in a virtual rainforest, while another VR experience called ‘Tree’ (Tree, 2017) transformed the users into a rainforest tree. VR can also simulate more transcendence-oriented experiences, such as near-death experiences (Barberia et al., 2018). Perhaps one of the greatest strengths of VR is the potential to experience different perspectives. Studying how this immersive reframing influences the users’ perceptions and behaviors requires measurements that quantify connective aspects of restoration.

Along with contemplation, biofeedback, and perspective-taking activities, other research paths lie in advancing modalities and implementing new modalities into restorative virtual environments, both sensory and non-sensory. Research with olfaction is only in the beginning phases, since 12% of the reviewed studies investigated scent. Further, the review showed plenty of opportunity for the advancement of auditory presentations through binaural, Ambisonic, and 3D recordings presented in noise-canceling headphones. For instance, only three (7%) reviewed studies reportedly used noise-cancellation in their experiments (bib.-Brownong.et.al.2020.Browning, Minnaugh, et al., 2020; Gerber et al., 2017, 2019; Gerber et al.2017;bib.Gerber.et.al.2019).

Considering the physiological effects of touching biophilic surfaces such as wood (Ikei, Song, & Miyazaki, 2017; Shen, Zhan, & Lian, 2020), studying haptics would be relevant in the context of restorative VR. Ultrasound is also a modality that could find some use in restorative VR, such as in simulating raindrops (Pittera, Gatti, & Obstir, 2019) or as non-sensory ultrasound neuromodulation (Blackmore, Shrivastava, Sallet, Butler, & Cleveland, 2019).

Finally, current research has mostly focused on green and sometimes blue spaces, omitting light’s vital role for health and well-being. Two exceptions are Li et al. (2020), who investigated the effects of brightness on stress recovery, and Anderson et al. (2017), who utilized a heat lamp in their VR environment. Light in its many forms could have significant potential for restoration, particularly in locations where natural sunlight is mostly absent for long periods each year. Some of the possibilities are far-infrared radiation to support recovery from physical exercise, as in some saunas (Mero, Tornberg, Mantykoski, & Puurtinen, 2015), and near-infrared and red light to promote tissue repair (i.e., Yadav & Gupta, 2017). The possibilities also include bright visible light to treat the seasonal affective disorder (Terman et al., 1989) and UV light for vitamin D synthesis and other health benefits (Juzeniene & Moan, 2012; Kalaian et al., 2017).

5.3. Limitations

This review has some limitations. For instance, the primary search method used for the descriptive analysis was Google Scholar. Google Scholar does not give replicable search results, which is a methodological constraint. However, we also searched the PubMed database to lessen the effect of this limitation. We may have missed some relevant research in our searches due to the research field’s interdisciplinary nature. In our defense, we strived to be comprehensive by using a combination of keyword searching, snowballing, and review article inclusion. We have confidence that the included studies give a reliable picture of the general practices in measures and modalities in the research fields.

Another limitation is that the primary author was solely responsible for data curation, i.e., data extraction from the reviewed papers and fitting the low-level measures to higher-level abstraction categories in the presented tables and model. The authors acknowledge that this is a methodological limitation and describe the article as an integrative narrative review rather than an integrative systematic review.
Accordingly, the paper’s aims are intended to provoke new discussion and research rather than present adjudicating evidence.

For future reviews, in addition to replicable search strategies and using multiple researchers for data extraction, we emphasize the importance of scoping experiments outside environmental psychology’s theoretical frameworks. Diverse fields such as media psychology, social psychology, biophysics, or photomedicine may include relevant literature that does not appear in restoration-related keyword searches. The review showed that at least studies on psychology, environmental science, medicine, and engineering are critical to consider when conducting a literature search for the topic.

Finally, we recognize that the proposed Multidimensional Model of Restoration Measurement is only an opening to further development in restoration theory. Extensive literature in ecopsychology (i.e., Roszak et al., 1995; Norton, 2009; Plesa, 2019), conservation psychology (i.e., Saunders, 2003; Clayton & Brook, 2005), and transpersonal psychology (i.e., Hartellius et al., 2007; Friedman & Hartellius, 2013) may prove helpful in further connecting the ecological and transcendental dimensions to the established restoration framework. There’s also a need to describe and evaluate the different measures in more detail. For instance, what are the pros and cons of different measures in a particular restoration dimension for a specific use case? Furthermore, the current model only presents measureable aspects. The model could later be extended with connections to different restorative modalities.

6. Conclusion

Research on restorative virtual natural environments is taking its first steps. The current limitations include, among others, a limited set of measurements, a lack of standardized measurement practices, and systems with only audiovisual modalities. We highlight the importance of integrating different theoretical approaches, holistic measurement, and investigation of the relationships between different kinds of measures. We have introduced the Multidimensional Model of Restoration Measurement as a template for comprehensive, contextually attuned measurement and future theory development. In particular, the connective dimensions could be utilized to study social interactions, ecological learning, and peak experiences in restorative environments. We believe that developing environments with new modalities, using biofeedback-assisted activities, and utilizing new perspective-taking designs are promising strategies for enriching the environments. We hold that the future of virtual natural environments lies in integrating sensory, nonsensory, and action-oriented modalities into one setting and studying restoration in both individual and connective aspects.

Declaration of competing interest

No competing financial interests exist.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.chb.2021.107008.

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