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Relaxing effects of virtual environments on the autonomic nervous system indicated by heart rate variability: A systematic review

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ABSTRACT

Recently, a number of virtual relaxation interventions (e.g., watching nature videos using virtual reality glasses) have been developed. Their effectiveness and factors influencing their success to induce physiological relaxation are unknown, however. This systematic review investigates first, whether virtual interventions can successfully induce changes in the autonomic nervous system associated with relaxation as measured by heart rate variability (HRV), and second, aims to determine whether specific intervention components exist which are necessary for their success. Online databases PubMed, Web of Science, and PsycInfo were included in the search. Out of 479 identified studies, 18 met the inclusion criteria, of which 17 found a significant physiological effect of a virtual relaxation intervention on HRV. Most used nature stimuli, either as pictures or videos, and assessed self-reported measurements in addition to HRV. Most studies also found an increase in HRV, with corresponding changes in various self-report measurements (e.g., decrease in anxiety). There was substantial heterogeneity between studies concerning the physiological outcome measures and details of the intervention. In summary, results from the included studies suggest that virtual relaxation interventions employing nature stimuli interventions are successful. Future studies should aim for a universal definition and operationalization of relaxation to allow easier comparison across different studies.

1. Introduction

1.1. Importance of relaxation

Relaxation is a necessary part of life. It contributes to psychological and physical regeneration, increases the quality of life and mental health (Smith et al., 2007), and serves as a protective factor against the negative effects of stress (e.g., on mental health; Bhasin et al., 2013). These positive effects of relaxation can be seen across the lifespan. In pediatric patients, relaxation leads to a decrease in frequency and intensity of headaches (Engel et al., 1992), and in older adults, it reduces depression and anxiety (Klainin-Yobas et al., 2015). Despite the importance of relaxation, there are still many open questions about the mechanisms by which relaxation has its effects, the associated affective changes, and moderating situational or personality factors. Since relaxation interventions differ greatly in the way they are implemented (e.g., yoga (Klainin-Yobas et al., 2015), massages (Meier et al., 2020), nature exposure (Farrow & Washburn, 2019), warm foot baths (Yamamoto & Nagata, 2011)) but also in duration (from 90-scond interventions (e.g., Igarashi et al., 2014) to programs spanning several weeks (e.g., Solberg et al., 2000)), it is at this point in time difficult to firm conclusions about overall success of the interventions, and possible moderating factors. A standardized relaxation protocol would enable an in-depth investigation of the mechanisms underlying the relaxation reaction and moderating factors, which would allow targeting bigger questions, for example the possibility of a blunted relaxation capability being linked to psychological diseases. First efforts have been undertaken towards standardized relaxation protocols, for example by standardized massage

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interventions in a laboratory setting (Meier et al., 2020). We conducted this systematic review to specifically investigate existing virtual relaxation interventions and their effectiveness since virtual interventions possess some important advantages. While standardization presents a difficulty when using real-life interventions (e.g., exposure to nature outdoor settings) it is relatively easy to standardize interventions based on virtual environments. Additionally, the implementation of virtual interventions is possible almost anywhere (e.g., in a university laboratory as well as a hospital room) needing relatively little space, not only allowing it to be transferred easily across different research environments but also possibly becoming part of standardized treatment interventions. The usage of virtual interventions is easy to implement since no specific training is needed, depending on the exact intervention it is as easy as launching a computer program. However, not only the variety of contents of virtual relaxation interventions is vast, ranging from virtual nature to games, but there is also a wide variety of other characteristics (e.g., duration, method of presentation) that could possibly modulate the effectiveness of an intervention. Therefore, a systematic review of the literature can potentially reveal which type of intervention is the most effective, enabling the development of a successful standardized relaxation protocol based on virtual environments. How relaxation is defined and measured should also be taken into account, since consistencies in used measurements would allow comparisons between different studies.

1.2. Definition of relaxation

Giving a conclusive definition of relaxation was not the focus and would thus be beyond the scope of this systematic review. Still, we suggest keeping physiological as well as psychological processes in mind when searching for a definition, as is done in recent research (Knaust et al., 2022). On the psychological level relaxation is experienced as a calm state of mind, with no worries or fear clouding the calmness (Steghaus & Poth, 2021). Pleasant emotions like happiness or contentment might be involved as well, though it is important to take the intensity of emotions into account. Even happiness experienced intensely is no expression of relaxation, since it can be associated with a high level of arousal (Knaust et al., 2022). Physiologically there is a relaxation of muscles (feeling warm and soft) as well as processes of the autonomic nervous system (increase in parasympathetic activity) that should be taken into account (Knaust et al., 2022). Another consideration, that to our knowledge has not been followed so far but could be examined closer, is a differentiation between state and trait relaxation, as it is with anxiety (Knowles & Olatunji, 2020) and mindfulness (Bravo et al., 2018). While relaxation as state could be induced in most of the participants with a successful intervention, looking at baseline level could show interindividual differences in trait relaxation. How exactly high levels of trait relaxation would influence state relaxation remains speculative and thus is not further considered in this systematic review.

1.3. Measuring relaxation

A prerequisite for a standardized assessment of relaxation is a universal measurement of relaxation to make results of different studies comparable. On the subjective experience level, there are many questionnaires used to measure affective states and changes, for example, the Positive Affect Negative Affect Schedule (PANAS; Watson et al., 1988) or the State-Trait Anxiety Inventory (STAI; Spielberger et al., 1971). Those questionnaires can assess the psychological aspects of relaxation but are likely influenced by confounding factors, like social desirability. Not only self-report questionnaires in general (Fisher & Katz, 2000) but also questionnaires about well-being specifically (Brajša-Žganec et al., 2011) are at risk of being distorted by social desirability. It seems that a decreased negative affect aligns with socially desirable answers (Brajša-Žganec et al., 2011). Since the definition of relaxation used in studies sometimes includes the reduction of negative affect this could bias results derived from self-report measurements.

On a physiological level, relaxation is tightly linked with the activity of the autonomic nervous system, consisting of the sympathetic nervous system (SNS) and the parasympathetic nervous system (PNS; McCorry, 2007). Increased parasympathetic activity is associated with relaxation and positive emotions, while increased sympathetic activity is associated with stress, anxiety, and the fight-flight response (Shaffer & Ginsberg, 2017). Thus, the autonomic state of relaxation should be associated with high parasympathetic activity. Although SNS and PNS are not reciprocal (see the autonomic space model; Berntson et al., 1993a), relaxation has often been observed to include states of low SNS as well. Thus, the ratio of SNS and PNS is also often employed to measure relaxation. For example, low SNS and high PNS activity can be observed when people start getting sleepy and during the first phase of sleep (Miglis, 2017). Since relaxation is associated with a feeling of calm, even up to drowsiness, it makes sense to find autonomic activity patterns during relaxation comparable to those during the first phase of sleep (Miglis, 2017).

To measure PNS activity, an effective and valid method is the determination of heart rate variability (HRV). HRV describes the beat to beat fluctuation of heart rate and is dominantly influenced by PNS (Acharya et al., 2006). There are various ways to calculate HRV, grouped into linear algorithms (time and frequency domain measures), nonlinear algorithms (fractal measures, entropy measures, symbolic dynamics measures, and Poincaré plot representations), and detrended fluctuation analyses (Francesco et al., 2012; Voss et al., 2009). These different measurements typically correlate highly with each other and can be influenced by either parasympathetic activity, sympathetic activity, or both (Voss et al., 2009). However, different measures are influenced by different branches of the autonomic nervous system and therefore, HRV measurements are not necessarily exchangeable. When interpreting results it is important to keep in mind, which branch(es) of the autonomic nervous system influence the HRV measurement, and which conclusions about PNS or SNS activation can consequently be drawn.

The most commonly used HRV measures are time and frequency domain measures (Billman, 2011). High frequency (HF) HRV is interpreted as a marker of PNS activity and low frequency (LF) HRV was originally regarded as a marker for SNS (Acharya et al., 2006; Quintana & Heathers, 2014). The interpretation of LF as purely influenced by SNS has been criticized extensively, as has the use of LF/HF ratio as a marker for sympathovagal balance (Quintana & Heathers, 2014): first, LF does not increase in situations of increased sympathetic activity (e.g., exercise), second, it is influenced by the PNS as well as the SNS. Thus, it should not be used as a marker for sympathetic activation (Billman, 2011) but a combination of SNS and PNS. HF is mostly considered to be solely influenced by the PNS (Acharya et al., 2006) and therefore often used as marker for the increase in parasympathetic activity associated with relaxation (e.g., Anderson et al., 2017; Kobayashi et al., 2018). Still, this interpretation of HF has also been criticized, arguing that sympathetic activity might influence HF after all (Billman, 2011). There is no final conclusion to this discussion and evidence is available for each claim. However, it seems safe to argue that there is a dominance of PNS on HF, and especially the contribution of PNS mediated respiration variation on HRV (respiratory sinus arrhythmia).

Together, the ongoing debate showcases the complexity of HRV parameters and their interpretation. In the end, HF is considered to be a valid marker for parasympathetic activity (Acharya et al., 2006; Shaffer & Ginsberg, 2017) but seems more strongly influenced by breathing depth and frequency (Quintana & Heathers, 2014). In contrast, time domain markers are less susceptible to distortion due to changes in breathing and, for example, body posture. The root mean square of successive differences (RMSSD) is a time domain marker, strongly correlated with HF, but less influenced by breathing (Acharya et al., 2006; Quintana & Heathers, 2014; Shaffer & Ginsberg, 2017).

Table 1 briefly summarizes all HRV markers used in the studies

Table 1
HRV indices used in included studies and their interpretation in relation to parasympathetic activity.

Measurement (times used in included studies)	Description	Influence of SNS and PNS	Effect of relaxation	Additional information	Correlation
Linear measurements					
Time Domain					
RMSSD (n = 4), (Bansal et al., 2009; Bertsch et al., 2012; Kleiger et al., 2005; Shaffer & Ginsberg, 2017)	Root mean square of the difference of successive RR intervals	Mostly influenced by PSN	Increase		HF, pNN50
SDNN (n = 4), (Bansal et al., 2009; Kim et al., 2018; Shaffer & Ginsberg, 2017)	Standard deviation of all RR intervals	SNS and PNS,	Increase	more accurate in 24h recordings, indicator for cardiac risk, low values mean stress	VLF, LF
NN50 (n = 1), (Bansal et al., 2009; Electrophysiology T.F. of the E.S. of C. the N.A.S. of P., 1996)	Adjacent RR intervals differing by more than 50 ms in entire ECG recording		Increase		HF
pNN50 (n = 3), (Bansal et al., 2009; Bertsch et al., 2012; Kim et al., 2018; Kleiger et al., 2005; Shaffer & Ginsberg, 2017; Shaffer & Venner, 2013)	proportion of successive RR intervals that are larger than 50ms	Closely correlated to PNS activity	Increase	low values mean stress, more reliable than SDNN in short term recordings	RMSSD, HF, ApEN
RRI (n = 1), (Byun et al., 2019; Choi et al., 2017)	time intervals between consecutive R-peaks	SNS and PNS	Increase	Decrease in reaction to stress (increase in SNS activity)	
SDSD (n = 2), (Bansal et al., 2009; Electrophysiology T.F. of the E.S. of C. the N.A.S. of P., 1996)	Standard deviation of differences between adjacent RR intervals		Increase		HF
Frequency domain					
VLF (n = 4), (Bansal et al., 2009; Shaffer & Ginsberg, 2017; Shaffer & Venner, 2013)	Power in very low frequency range (0.003 Hz–0.04 Hz)	PNS and SNS (probably stronger PNS influence)	Increase		SDNN
LF (n = 10), (Bansal et al., 2009; Kim et al., 2018; Shaffer & Ginsberg, 2017)	Power in low frequency range (0.04 Hz–0.15 Hz)	PNS and SNS	Decrease	high values interpreted as low PNS activity	
HF (n = 10), (Bansal et al., 2009; Bertsch et al., 2012; Kim et al., 2018; Shaffer & Ginsberg, 2017)	Power in high frequency range (0.15 Hz–0.4 Hz)	PNS	Increase	low values associated with stress, panic anxiety worry; influenced by breathing	RMSSD, NN50, pNN50, SDSD, ApEN
LF/HF (n = 10), (Bansal et al., 2009; Kim et al., 2018; Shaffer & Ginsberg, 2017; Shaffer & Venner, 2013)	Ratio of low and high frequency	SNS and PNS	Decrease	Low values mean PNS dominance (conserve energy); high values mean SNS dominance (stress), This interpretation has been heavily criticized (Billman, 2013)	
Nonlinear measurements					
Entropy					
ApEN (n = 1), (Acharya et al., 2006; Voss et al., 2009)	Approximate entropy, index for the overall complexity and regularity of time series		Increase		RMSSD, pNN50, HF
SampEN (n = 1), (Voss et al., 2009)	Sample entropy, conditional probability that two sequences of m consecutive data points that are similar to each other		Increase		negatively correlated with LF and LF/HF
FuzzEN (n = 1), (Liu et al., 2013)	Fuzzy Entropy, Improvement of SampEN and ApEN, focus on the local characteristics of the sequence		Increase		
ShanEN (n = 1), (Byun et al., 2019; Dua et al., 2012)	Shannon entropy, sum of entropy computed over the entire frequency range		Increase	Reduced in stress and increased in relaxation in healthy participants	

Notes: SNS = sympathetic nervous system, PNS = parasympathetic nervous system. For some markers no sources could be found describing which ANS branch(es) influence the marker. Those cells are left empty.

included in this review, as well as the autonomic branch(es) mostly influencing the marker, changes in association with relaxation, and positive correlations with other markers included in this table.

1.4. Virtual relaxation

As described above (see 1.1), mechanisms and effectiveness of standardized relaxation protocols in virtual environments are largely unexplored. This is despite the fact that in recent years, an increased interest in virtual methods to induce relaxation could be observed. This can, for example, be seen in the increasing number of studies researching this topic. The online database PubMed lists 728 results for the search term "virtual relaxation", with an increase in articles especially in recent years (see Fig. 1), going up from 29 results in 2012 to 112 results in 2021 (PubMed, 29.12.2022).

These studies include various employment methods of virtual relaxation, for example, computer screens, head-mounted displays (HMD, see Fig. 2a), which consists of either two small screens or one screen showing separate images for each eye. While applications are allowing a smartphone to be used as an HMD, it only shows one picture (Rebenitsch & Owen, 2016). Some studies use a cave system, projecting images onto walls and sometimes the floor, creating a virtual environment (de Back et al., 2020; see Fig. 2b). While every method of presentation has advantages and disadvantages, they all can be used to induce relaxation in research settings (e.g., Annerstedt et al., 2013) and sometimes in therapeutic settings as well (e.g., Veling et al., 2021).

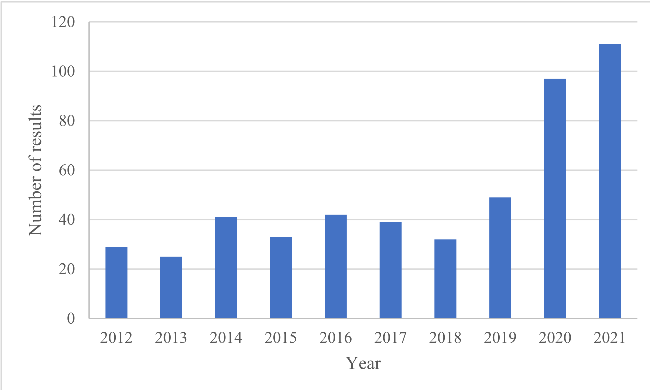


Fig. 1. Increase of results in the online database PubMed for the search term "virtual relaxation" from 2012 to 2021.

For example, using a computer screen and pictures of urban and natural environments, Gladwell et al. (2012) found an increase in HRV associated with an increase in subjective relaxation when participants viewed nature environments compared to urban environments. Using a cave system to expose participants to a virtual Trier Social Stress Test followed by a recovery phase in a virtual forest showed a faster recovery measured by an increase in HRV in a virtual forest with sounds compared to a virtual forest without sounds, or a normal room (Annerstedt et al., 2013). Besides the pure display of relaxation environments, some studies add biofeedback to the virtual environment (e.g., Rockstroh et al., 2019). Biofeedback uses physiological signals (e.g., heart rate, skin temperature) presented to the user in real-time to improve the understanding of physiological activities and positively influence health (Schwartz, 2010). Those physiological signals can be either presented as numbers (e.g., real-time heart rate) or can be integrated into the virtual environment. Integrated biofeedback has thereby, for example, been shown to help patients with generalized anxiety disorder to train relaxation techniques (Riva et al., 2010). In this particular study, there was a biofeedback component within the virtual environment, for example, a campfire changed in size according to the participant's heart rate.

1.5. Advantages of virtual nature exposure

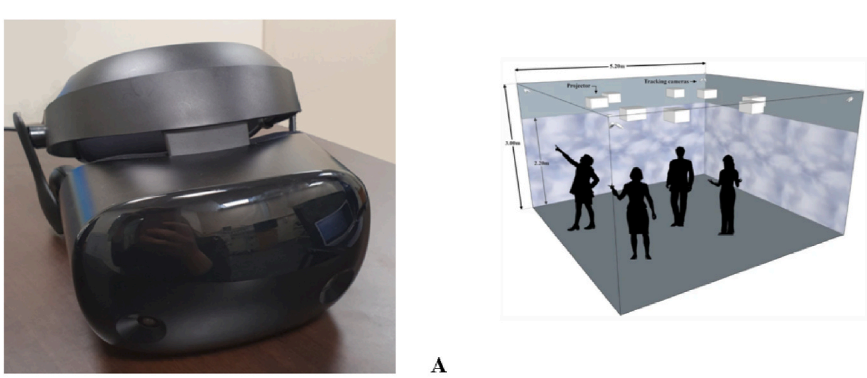
It appears that on a subjective experience level, studies using virtual environments can successfully induce relaxation. It is at this point however unclear whether these findings extend to the physiological level. Exposure to nature environments in real-life settings appears to have these effects. For example, a walk in a forest is associated with increased HRV (HF), reduced blood pressure, and decreases in heart rate (Kobayashi et al., 2018; Payne & Delphinus, 2019). If these effects would extend to virtual environments, it would hold a number of important advantages for their use in therapeutic settings. Virtual environments allow a wide range of stimuli a patient can be safely exposed to, while physically remaining in secure surroundings. Virtual environments can further be used in almost all circumstances, as long as hard- and software requirements are met. Every aspect of the environment can be controlled, allowing standardization across participants (as opposed to, for example, a sudden change in weather when walking in a real forest). These advantages are especially important when aiming for standardized interventions in research settings.

1.6. Aim of the current systematic review

Riches et al. (2021) conducted a systematic review concerning the feasibility, acceptability, and effectiveness of relaxation interventions using a HMD. While they found a successful increase in relaxation in most studies, they did not distinguish between the different ways to measure relaxation, e.g., heart rate, HRV, and self-report measurements (e.g., PANAS, Brief Profile of Mood States). While these results show that virtual relaxation interventions are promising, they do not allow conclusions about the effects of virtual relaxation on the autonomic nervous system specifically.

Therefore, the present review focused on studies that measured HRV as a marker of the autonomic nervous system to investigate, whether physiological relaxation can be successfully induced using virtual relaxation interventions. To be able to derive the effect of virtual environments exclusively, studies using paced breathing were excluded. Paced breathing describes an exercise, where breathing patterns are synchronized to an external pacemaker (e.g., audio or visual), with varying (6–15) breathing cycles per minute (Szulczewski, 2019). Since there is a close relationship between breathing and especially frequency-domain measures of HRV (Shaffer & Ginsberg, 2017), paced breathing increases HRV, making it impossible to determine if the virtual environment alone affected HRV. Different presentation methods will be considered in this study since they vary in difficulty to use and financial costs. To find the most effective but at the same time, least cost intensive method it is important to consider the implementation difficulty of a given relaxation intervention. In addition, the possibility to interact with individual virtual environments will be included as another focus of this review as well. Even though self-report measurements do not necessarily mirror changes in the autonomic nervous system associated with relaxation, they are frequently used to measure psychological relaxation, so this systematic review will consider and report on them as well.

In summary, this systematic review aims to answer the following questions.



A (Kim et al., 2021)

B (de Back et al., 2020)

Fig. 2. Exemplary pictures of a head-mounted display (A) and a cave system (B).

1. Are HRV parameters reflective of PNS activity increased when participants are exposed to virtual relaxation environments? Are these changes dependent on (i) the possibility to interact with the environment, or (ii) on inclusion of biofeedback components in the virtual environment?
2. Is the effect of virtual relaxation interventions on HRV dependent on different applications of virtual presentation (e.g., head-mounted displays, computer screens)?
3. Do virtual environments successfully increase self-reported relaxation?

2. Methods

2.1. Protocol and search strategy

This systematic review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA; Moher et al., 2009). A protocol was written following the PRISMA-P guidelines (Preferred Reporting Items for Systematic Review and Meta-Analysis Protocols; Moher et al., 2015) and registered at the International Prospective Register of Systematic Reviews PROSPERO on 10.11.2021 and updated on 28.01.2022 (ID CRD42021290162; https://www.crd.york.ac.uk/PROSPERO/display_record.php?RecordID=290162.)

The online databases PubMed, Web of Science, and PsycInfo were searched for the last time on 28.01.2022. The following search terms were used for all three databases: (vr OR virtual reality OR virtual OR screen OR cave OR 360° OR video OR picture) AND (hrv OR heart rate variability) AND relaxation. No study design or language limits were imposed on the search. Results of the search were uploaded to the online tool for systematic reviews CADIMA (version 2.2.1; https://www.cadima.info/; Kohl et al., 2018). Using CADIMA duplicates were removed. Subsequently, title and abstract were screened for eligibility according to the predefined criteria, followed by a full-text screening (see Fig. 3 for an overview of the procedure).

2.2. Inclusion and exclusion criteria

Articles were included in this review if they (i) reported original data, (ii) included human participants, (iii) used virtual interventions to promote relaxation, and (iv) measured at least one HRV marker in reaction to the relaxation intervention. All presentation methods for virtual environments (e.g., screen, HMD) were included. Articles in German or English were included. Studies using the virtual environment to promote a paced breathing intervention were excluded. Studies not giving information about the presentation method or the changes in HRV in reaction to the virtual relaxation intervention were excluded without contacting the authors beforehand.

Data were screened for the characteristics of the sample (number, age, sex) and details about the virtual intervention. This included presentation method, type of virtual environment (e.g., nature pictures, games), possibility to interact with the virtual environment (e.g., by using controllers), or biofeedback adaptions. The main outcome of interest were the changes in all HRV measures in reaction to the relaxation intervention. If no information about interaction with the virtual environment was provided, we assumed that neither biofeedback nor another kind of interaction was incorporated. As an additional outcome, the influences of virtual relaxation interventions on subjective self-report measurements (e.g., PANAS) are presented if such measurements were assessed in the included studies. 18 studies met the inclusion criteria (see Fig. 3).

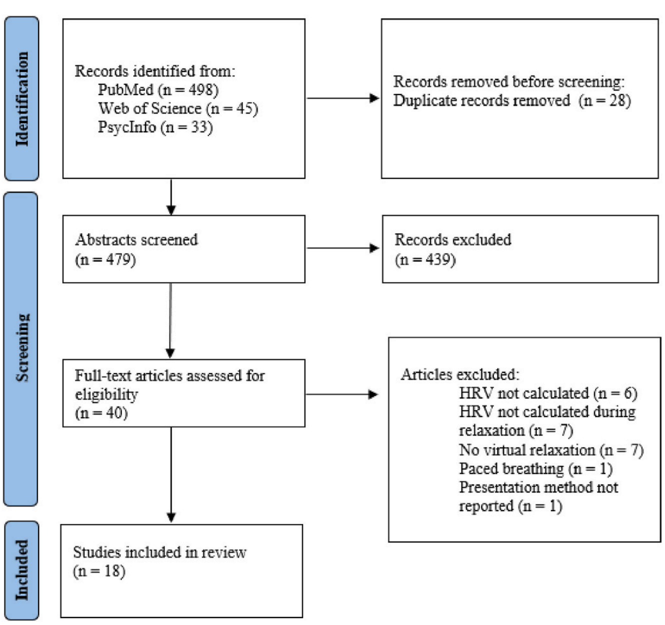


Fig. 3. Flow diagram for the study selection process. Adapted after Page et al. (2021).

2.3. Quality assessment

To assess the risk of bias in individual studies the Cochrane risk of bias tool for randomized trials (sequence generation, allocation concealment, blinding, incomplete outcome data, and selective reporting) was used (Chapter 8 in the Cochrane Handbook for Systematic Reviews of Interventions; Higgins et al., 2019). For each of the subscales, the risk of bias with each study is rated as low, unclear, or high. The assessment was done independently by two researchers (RJG and KEK) at study level. Afterward, the researchers came together to reach a consensus regarding the rating. In case of no success in reaching a consensus a third researcher (JCP) would have been consulted.

2.4. Summary strategy

Data from the included studies were summarized. Effects of the virtual relaxation interventions on HRV were summarized, separated into each of the three subgroups: with interaction, with biofeedback, and without interaction. A special focus was put on whether changes in HRV can be interpreted as an increase in physiological relaxation. Effects on subjective self-report measurements were summarized within the subgroups.

In the systematic review protocol, it was stated that meta-biases will be addressed with a funnel plot and the Grading of Recommendations Assessment, Development and Evaluation (GRADE) will be used to assess the confidence in the found evidence. Since there is a huge heterogeneity between the included studies concerning outcome HRV measurements and interventions, we chose to omit these analyses. This paper thus presents a systematic review without additional meta-analyses.

3. Results

3.1. Included studies

A list of the included studies with authors and journal, sample description, presentation method, interaction possibility, details about the virtual relaxation intervention, HRV measurements, HRV results, and results of self-reported questionnaires is shown in Table 2. First the studies that gave no possibility to interact with the virtual environment are included in the table, followed by those with interaction possibilities and those with biofeedback.

Table 2
Table of included studies.

Citation and Journal	Sample (N, age *M*±*SD*)	Presentation method	Interaction	Virtual relaxation intervention	HRV measurements	HRV results [a]	Self-report results [a]
Studies without interaction possibilities							
(Matsui et al., 2016), Journal of medical engineering & technology	MDD: 13 (7f), 41 ± 12; healthy: 28 (13f), 40 ± 12	Screen	No	10min; nature pictures (waterside) with relaxing sounds	LF, HF	HF: decrease after relaxation in MDD patients, increase after relaxation in healthy controls	n.a.
(Byun et al., 2019) Technology and Health Care	MDD: 33 (24f), 40.18 ± 16.10; healthy: 33 (24f), 40.21 ± 15.16	Screen	No	5min; nature pictures (stress before)	ApEN, SampEN, FuzzEN, ShanEN, RRI	No group effect: increase in RRI, FuzzEN, and ShanEN	n.a.
(Igarashi et al., 2014) Cognitive processing	19 (0f), 22.2 ± 0.6	Screen (dome)	No	90sec; a picture of water lily, 2D and 3D, within design	LF, ln(HF), ln (LF/HF)	Ln(LF/HF) higher while viewing the 3D picture	n.a.
(Gaggioli et al., 2020) Annual Review of Cybertherapy and Telemedicine	47 (31f), 26.0 ± 7.9	HMD	No	Computer-generated garden with relaxation narrative and music or resting control (stress before)	RMSSD	RMSSD: increase in both groups	STAI: stronger reduction of anxiety after VR garden compared to control
(Liszio et al., 2018) Annual Review of Cybertherapy and Telemedicine	62 (36f), 22.6 ± 5.36	HMD and screen	No	9min; a computer-generated underwater world with sound, HMD, or screen or waiting (stress before)	SDSD	SDSD: increase in VR group, decrease in screen and waiting group	STAI: strongest decrease of anxiety in VR group; PANAS: increase in positive affect in VR group, a decrease of negative affect in VR and screen group; IPQ: highest scores in VR group
(Anderson et al., 2017) Aerospace medicine and human performance	18 (9f), 32 ± 12	HMD	No	15min; 360° videos, rural Ireland with sound, Australian beaches with sound and music and heat lamp, control indoor classroom (stress before), within design	LF, HF, LF/HF	*Beach*: HF higher during VR compared to stress and baseline, LF/HF lower during VR compared to stress and baseline; *Ireland*: LF lower at the beginning than during stress, HF higher during VR compared to stress; *Control*: LF lower during stress than at beginning of VR, HF higher during VR compared to stress, LF/HF decreased during VR and lower compared to baseline	MRJPQ: lower scores for control room
(Tonacci et al., 2020) Processes	24 (19f), 27.4 ± 5.5	Screen	No	3min30sec; video about yoga with sound and color of chakra, then same video only sound or only video	SDNN, pNN50, LF, HF, LF/HF	SDNN decreased during only video compared to rest	Only video: reduction of anxiety in STAI and VAS; only audio: reduction of anxiety in VAS
(Huang et al., 2016) Research in gerontological nursing	30 (15f), 63.87 ± 7.56, with depressive symptoms	Screen	No	30min; sedative or stimulative music videos (Taiwanese folk songs), within design	LF/HF	LF/HF shows a treatment effect in both groups (decrease)	Reduction of depressive symptoms after both video conditions (GDS)
(Tsutsumi et al., 2017) Japan Journal of Nursing Science	12 (0f), 22.2 ± 1.7	Screen	No	15min; video of sea and forest, 15min full video then 15min only sound (eyes closed), within design	LF, ln(HF)	HF: average higher during sea than forest, higher for sea preference group in general, increase in forest preference group strongest	POMS: mood improvement (confusion, vigor) after both videos for the sea preference group
(Santarcangelo et al., 2012) International journal of psychophysiology	46 (25f), 19–30 years	Screen	No	30min; relaxation video (landscapes with music) or threatening (shining), within design	VLF, LF, HF, LF/HF	HF higher and LF/HF lower in females compared to males; during nature video: VLF and LF/HF decrease and HF increases	Increase in reported relaxation after nature video

(continued on next page)

Table 2 (*continued*)

Citation and Journal	Sample (N, age *M*±*SD*)	Presentation method	Interaction	Virtual relaxation intervention	HRV measurements	HRV results [a]	Self-report results [a]
Citation and Journal	Sample (N, age *M*±*SD*)	Presentation method	Interaction	Virtual relaxation intervention	HRV measurements	HRV results [a]	Self-report results [a]
Studies with interaction possibilities							
(Liszio & Masuch, 2019) Annual Review of Cybertherapy and Telemedicine	57 (41f), 23.7 ± 5.67	HMD	Yes	9min; interactive VR (mini-games) and non-interactive VR (same environment) and control	SDSD	SDSD: increase during interactive VR, decrease during non-interactive VR	STAI: lower anxiety during interactive VR compared to control; IPQ: a higher feeling of presence in interactive VR compared to non-interactive VR)
(Russoniello et al., 2009a) Annual Review of Cybertherapy and Telemedicine; (Russoniello et al., 2009b) Journal of CyberTherapy & Rehabilitation [b]	134 (57f), mean age 24	Screen	Yes	20min; participants choose one mini-game or control (internet search), bejeweld2 (matching sequence, n = 38), peggle (pinball game, n = 36), bookworm (crossword, n = 29)	VLF, LF, HF, LF/HF	Increase in relaxation in all markers after all games, compared to control bejeweld2 players show a decrease in VLF and increase in LF and LF/HF	POMS: decrease in tension, depression, fatigue, confusion, and anger after all games compared to control, increase in vigor after all conditions (bejeweld2 higher than control)
Citation and Journal	Sample (N, age *M*±*SD*)	Presentation method	Interaction	Virtual relaxation intervention	HRV measurements	HRV results [a]	Self-report results [a]
Studies with biofeedback							
(Rockstroh et al., 2019) International Journal of Human-Computer Studies	69 (41f), 22.9 ± 4.0	HMD	BF	10min; 2D-BF with abstract graphical indicators or VR-BF with changes in the environment (e.g., clouds); no treatment control	RMSSD, SDNN, LF/HF	RMSSD: increased during the intervention in all groups; SDNN and LF/HF: during intervention both BF groups were higher than control	MDBF: more positive mood after intervention and both BF groups compared to control; motivation (VAS): highest for VR-BF; attention (VAS): highest in VR-BF group
(Kim et al., 2021) Frontiers in psychiatry; (Kim & Jeon, 2021) 15th International Conference on Ubiquitous Information Management and Communication (IMCOM) [b]	83 (43f), 38.53 ± 11.8 years	HMD	BF	10min30sec; virtual nature with soundtrack, with (VR) and without (BF) BF (stress before), within design	RMSSD, SDNN, pNN50, NN50; VLF, LF, HF, LF/HF	VLF: decrease in BF; LF and HF: increase in VR; NN50 and pNN50: decrease in VR and BF; SDNN and RMSSD: increase in BF	STAI and pain (NRS): lower after BF and VR
(Parnandi & Gutierrez-Osuna, 2015) 2015, IEEE Journal of biomedical and health informatics	25 (10f), 19–33 years	Screen (smartphone)	BF	8min; game (bubble shoot) with BF (games gets easier when more relaxed), BR or RMSSD or EDA for BF or no BF (stress before)	RMSSD	RMSSD increased during the game with BR-BF, decreased during the game with no BF	n.a.
(Parnandi & Gutierrez-Osuna, 2017) IEEE Transactions on Affective Computing	14 (9f), 19–31 years	Screen (smartphone)	BF	30min; game (bubble shoot) with BR-BF, BF as numerical representations or game changes or both or none (stress before)	SDNN, pNN50; LF, HF, LF/HF	n.s.	n.a.

Abbreviations: f = female, HMD = head mounted display, BF = biofeedback, MDBF = Mehrdimensionaler Befindlichkeitsfragebogen („*German Multidimensional Mood Questionnaire*"), VAS = visual analogue scale, RMSSD = root mean square of successive differences, SDNN = standard deviation of all normal-to-normal intervals, LF = low frequency heart rate variability, HF = high frequency heart rate variability, VLF = very low frequency heart rate variability, pNN50 = proportion of successive RR intervals that are larger than 50ms, ApEN = Approximate entropy, FuzzEn = Fuzzy Entropy, ShanEn = Shannon entropy, NN50 = successive RR intervals differing by more than 50 ms, STAI = State trait anxiety scale, NRS = numeric rating scale, VR = virtual reality, MDD = major depression disorder, RRI = time interval between consecutive R-peaks, SampEN = Sample entropy, SDSD = standard deviation of successive differences, PANAS = Positive And Negative Affect Schedule, IPQ = Igroup Presence Questionnaire, MRJPQ = Modified Reality Judgment and Presence Questionnaire, BR = breathing rate, EDA = electrodermal activity, POMS = Profile of Mood States, ln() = natural logarithm, GDS = Geriatric Depression Scale, n.a. = not assessed.

[a] Only significant results will be presented in this table.

[b] Article and conference paper on the same sample, will be considered at as one study for this systematic review.

3.2. Risk of bias rating

The risk of bias was rated on study level independently by two researchers (RJG and KEK), using the Cochrane risk of bias tool (Chapter 8, Higgins et al., 2019). Following this tool, the criteria sequence generation, allocation concealment, blinding, incomplete data, and selective outcome reporting were used. Sequence generation describes the randomization of allocation sequence to avoid selection bias (e.g., assigning the participants to different intervention groups on the basis of a coin toss). Allocation concealment does not refer to the way the allocation is generated but if it was adequately concealed from participants and experimenters. If participants are aware of their allocation, they also are aware of the different parts of the experiment and knowing what will happen next might influence their behavior in preceding parts of the experiment (e.g., knowing that a stressor is next could increase tension beforehand). Not only participants but also personnel should be blinded concerning outcome measures and interventions. Incomplete outcome data should be addressed, for example reasons for participants dropping out. Selective reporting is given if, for example, only significant effects are reported even though additional measurements were assessed. For each criterion, the risk of bias was rated as high, low, or in case of insufficient information, as unclear (see Fig. 4). The ratings for a high risk of bias stemmed from inadequate allocation concealment (e.g., participants knew that a stress test would be part of the experiment when they underwent the relaxation intervention) or unexplained dropout (e.g., why and how many participants of each group were not part of the final analyses). Since no study had more than one high risk of bias rating, we chose to include all in the data synthesis.

3.3. Effects on HRV of interventions without interaction possibilities

Of the 18 included studies the majority of ten studies did not offer any kind of interaction possibilities for the participants Of those eight studies used nature pictures or videos (e.g., water lily, beach, forest, underwater; Anderson et al., 2017; Byun et al., 2019; Gaggioli et al., 2020; Igarashi et al., 2014; Liszio et al., 2018; Matsui et al., 2016; Santarcangelo et al., 2012; Tsutsumi et al., 2017), one study used music videos (Huang et al., 2016) and one study used a video about yoga and chakras (Tonacci et al., 2020). All ten studies found an effect of their respective virtual relaxation intervention on the measured HRV indices, indicating an increase in relaxation (e.g., an increase in HF or RMSSD). However, this seemed to be an unspecific effect on relaxation after a stressor in some studies. Gaggioli et al. (2020) found an increase in RMSSD after a stressor in the treatment group, viewing a

Fig. 4. Risk of bias rating for individual studies. Created using robvis (McGuinness & Higgins, 2021; https://mcguinlu.shinyapps.io/robvis/).

computer-generated garden with a relaxation narrative and music, as well as in the control group, who relaxed in a chair without a virtual intervention. Anderson et al. (2017) found increased physiological relaxation (increase in HF) after a stressor when participants watched two sets of virtual nature environments (rural Ireland and Australian beach) and while watching the control environment, an indoor classroom. This hints at a general, unspecific relaxation effect of virtual environments. Other studies showed an increase in relaxation in reaction to watching a 30 min nature video (increase in HF; Santarcangelo et al., 2012) or watching music videos for 30 min (decrease in LF/HF; Huang et al., 2016) without a preceding stressor.

Individual differences seem to influence the reaction to virtual relaxation interventions. Tsutsumi et al. (2017) found the preference for either forest or the sea to change their participants' reaction to a 15 min long video of those landscapes. While watching the forest video the sea preference group had higher HF values at baseline and during the video, but the increase in HF while watching the video was stronger in the forest preference group, even though the total HF values remained below those of the sea preference group during the whole video.

Furthermore, psychopathology also seems to play a role. In general, mental illnesses are associated with lower baseline HRV values (Acharya et al., 2006; Shaffer & Ginsberg, 2017). However, the lower baseline does not necessarily affect the magnitude of the response, yet results are inconclusive at this point. Matsui et al. (2016) found a decrease in HF in patients with major depressive disorder after watching nature pictures for 10 min but an increase in HF in healthy participants. In contrast, Byun et al. (2019) found no group differences between patients with a major depressive disorder and healthy participants in reaction to viewing nature pictures for 5 min after a stressor (ApEN, SampEN, FuzzEN, ShanEN, RRI). Methodological differences between those two studies make it difficult to compare their results (different HRV indices, different length of exposure to nature pictures, with and without preceding stressor). Accordingly, more research is needed to better understand the effects of psychopathology on the relaxation reaction.

3.4. Effects on HRV of interventions with interaction possibilities

Two studies gave their participants the possibility to interact with the virtual world without using biofeedback. Again, both studies found an effect on HRV indices in reaction to their respective interventions.

Russoniello et al. (2009a) and Russoniello et al. (2009b) are two records referring to the same study whereas Russoniello and collegaues (2009a) report only partial results. In the context of this review, we will look at them together. The study compared 20 min playing a mini-game (matching sequence, pinball game, or crossword) with an internet search activity (searching for articles about health and saving them in a folder). Participants in the game condition could choose one of three mini-games to play. They found a decrease in VLF and an increase in LF and LF/HF when playing the matching sequence game compared to an internet search. They interpreted those results as a stronger decrease of physical stress in reaction to the video game. However, those results cannot be interpreted as an increase in relaxation as defined by an increase in parasympathetic activity. LF is influenced by both SNS and PNS, thus an increase in LF might represent an increase in SNS activity.

Liszio and Masuch (2019) compared being exposed to 9 min of a virtual beach, presented via HMD, with (interactive group) or without (non-interactive group) integrated mini-games (e.g., throwing coconuts into a box) with 9 min of a waiting control condition. They found an increase in SDSD activity in the interactive group and a decrease in SDSD in the non-interactive group. This shows, that interacting actively with the virtual reality environment can enable physiological relaxation, in comparison to non-interactive alternatives, hinting at an influence of interaction possibilities on the effects a virtual relaxation intervention has on HRV.

3.5. Effects on HRV of interventions with biofeedback

Four studies used biofeedback in their virtual relaxation intervention. One study using smartphone screens as presentation method (Parnandi & Gutierrez-Osuna, 2017) failed to find significant effects of their intervention (mini-game on smartphone screen "Frozen Bubble" with breath rate biofeedback) on any of the assessed HRV indices (SDNN, pNN50, LF, HF, LF/HF). In contrast, the other study using a smartphone mini-game to transport biofeedback did observe effects on HRV parameters (Parnandi & Gutierrez-Osuna, 2015). Their participants played a bubble shoot mini-game ("Frozen Bubble", shooting colored bubbles into a line of colored bubbles, bubbles disappear when enough of the same color are next to each other) for 8 min, either with or without biofeedback. Three physiological measures were used for the biofeedback: breathing rate, HRV (RMSSD), or electrodermal activity. When an increase in relaxation was detected (e.g., increase in RMSSD or slower breathing rate) the game got easier for the participants. RMSSD increased during the game in the breathing rate biofeedback group and decreased in the group without biofeedback. This indicates, using breathing rate as a biofeedback marker might be more successful than other physiological markers, since breathing rate can be more easily controlled by participants than, for example, electrodermal activity. The decrease of RMSSD during the mini-game without biofeedback indicates, that a game alone might not lead to an increase in PNS activity and corresponds with the results by Russoniello et al. (2009b, 2009a).

Kim et al. (2018) and Kim and Jeon (2021) provided two publications based on the same experiment and sample, therefore we will consider them as one in the context of this systematic review. They used virtual nature with and without biofeedback after a stressor. In reaction to the biofeedback version, there was a decrease in VLF, nn50, and pNN50 and an increase in SDNN and RMSSD. In reaction to the no-biofeedback version, they found a decrease in NN50 and pNN50 and an increase in LF and HF. These results are puzzling however, since RMSSD and pNN50 are usually positively correlated (Shaffer & Ginsberg, 2017). If anything, this emphasizes that there are different factors influencing the various HRV indices to different degrees, and even though some of the indices correlate with each other, they may still show significant interindividual variation. Nevertheless, the changes in HRV in reaction to both virtual environments can be interpreted as an, at least partly, increase in physical relaxation (as seen by the increase in RMSSD in reaction to the biofeedback version, and the increase in HF in reaction to the non-biofeedback version).

Rockstroh et al. (2019) used a 10 min long biofeedback session, either visualized by abstract graphical indicators (a circle changing colors) or by changes in the virtual environment (e.g., the density of clouds on the beach) compared to a waiting control group. RMSSD increased in all three groups, while SDNN and LF/HF only increased in the two biofeedback groups. This suggests that biofeedback influences HRV in general, regardless of how it is presented.

3.6. Influences of presentation method on intervention's effects on HRV

Of the studies without interaction possibilities, eight used a computer or smartphone screen (Byun et al., 2019; Huang et al., 2016; Igarashi et al., 2014; Liszio et al., 2018; Matsui et al., 2016; Santarcangelo et al., 2012; Tonacci et al., 2020; Tsutsumi et al., 2017) and three used a HMD (Anderson et al., 2017; Gaggioli et al., 2020; Liszio et al., 2018) as the method of presentation. Looking at interventions with interaction possibilities, one study used computer games (matching sequence, pinball game, or crossword) played on a screen (Russoniello et al., 2009a; 2009b), and one study used a HMD with and without the possibility to interact with the environment (Liszio & Masuch, 2019). Of the studies with biofeedback interventions two used HMDs (Kim et al., 2018; Kim & Jeon, 2021; Rockstroh et al., 2019), and two used smartphone screens (Parnandi & Gutierrez-Osuna, 2015, 2017). In summary, the majority of 11 studies used screens (computer or smartphone) while six studies used a HMD. A possible explanation for the apparent preference for the usage of screens could be the lower costs and the advantage of more experience in using them compared to HMDs.

While different applications of virtual presentation were used in the included studies only Liszio et al. (2018) compared the effects of a virtual relaxation intervention using a computer screen or an HMD directly. Participants viewed a computer-generated underwater world for 9 min after a stressor. The control group waited for 9 min in a chair. Relaxation increased only in the HMD group (increase in SDSD), while it decreased in the screen and waiting control groups. This finding indicates that a more realistic method of presentation (e.g., HMD is more realistic than PC screens, since the virtual environment is the only thing visible) is important for a successful increase in relaxation. Additionally, the only included study not finding a significant effect on HRV indices (SDNN, pNN50, LF, HF, LF/HF) used a smartphone screen (Parnandi & Gutierrez-Osuna, 2017) to present their intervention (mini-game on smartphone screen "Frozen Bubble" with breath rate biofeedback). Being the smallest screen used this could indicate that smartphone screens are allowing too many impressions besides the intervention to distract participants, highlighting the advantage of other applications like HMDs.

3.7. Effects on self-report measures of interventions without interaction possibility

Considering subjective ratings of the interventions without interaction possibilities, two assessed self-reported anxiety with the STAI (Gaggioli et al., 2020; Liszio et al., 2018) and one via a virtual analog scale (Tonacci et al., 2020), two assessed affect (PANAS; Liszio et al., 2018) or mood (Profile of Mood States, POMS; McNair et al., 1981 in Tsutsumi et al., 2017), two assessed presence in the virtual environment (Igroup Presence Questionnaire, IPQ; Schubert et al., 1999 in Liszio et al., 2018 or Modified Reality Judgment and Presence Questionnaire, MRJPQ; Witmer & Singer, 1998 in Anderson et al., 2017) and one each assessed depressive symptoms (Geriatric Depression Scale, GDS; Lee et al., 1993 in Huang et al., 2016) and self-reported relaxation (Santarcangelo et al., 2012). Three studies didn't assess any kind of self-reported measurement (Byun et al., 2019; Igarashi et al., 2014; Matsui et al., 2016). The subjective changes in self-report measurements were sometimes not associated with changes in HRV. For example, while RMSSD showed an increase in the virtual relaxation intervention group as well as the waiting control group, anxiety scores (STAI) were more strongly reduced in the intervention group (Gaggioli et al., 2020). Still, most studies showed changes in self-report measurements to be in line with changes in HRV. Watching the underwater world via the HMD increased SDSD, decreased anxiety (STAI) and negative affect, and increased positive affect (PANAS) (Liszio et al., 2018). Reported relaxation increased alongside HF after watching a video showing landscapes (Santarcangelo et al., 2012).

3.8. Effects on self-report measures of interventions with interaction possibility

Both studies reporting interventions with interaction possibilities (Liszio & Masuch, 2019; Russoniello et al., 2009a, 2009b) assessed additional self-reported measurements. Comparing the interactive version of the virtual beach with the waiting control group, lower anxiety scores (STAI) were found in the interactive group (Liszio & Masuch, 2019). This is consistent with the assessed increase in SDSD. Additionally, subjects in the interactive version group reported higher levels of presence (IPQ) than the non-interactive version. This is the second study included in this systematic review, although from the same group of authors, that found higher IPQ scores associated with an increase in physiological relaxation (increase in SDSD in both studies; Liszio et al., 2018; Liszio & Masuch, 2019). The experiment using mini-games played on a screen (Russoniello et al., 2009a; 2009b), found positive changes in the POMS (e.g., decrease in tension and depression, increase in vigor) after all mini-games. Even though participants did not play complicated games, an increase in vigor was observed, which could be associated with the increase in SNS activity as measured by changes in HRV indices.

3.9. Effects on self-report measures of interventions with biofeedback

Both studies including biofeedback in a smartphone mini-game did not assess any additional self-reported questionnaires (Parnandi & Gutierrez-Osuna, 2015, 2017). Kim and colleagues (Kim et al., 2018; Kim & Jeon, 2021) found a decrease in both, anxiety (STAI) and pain (number rating scale) after their virtual intervention with and without biofeedback. Rockstroh et al. (2019) found an increase in positive mood assessed via the German Multidimensional Mood Questionnaire (MDBF, Steyer et al., 1997) after both biofeedback versions. However, they found higher scores for motivation and attention (both visual analog scales) when biofeedback was presented as changes in the virtual environment compared to abstract graphical indicators. Even though both biofeedback versions were similar in their effect on HRV, this difference in motivation and attention can be of importance when considering using biofeedback as a treatment, since motivated patients are more likely to complete treatment.

4. Discussion

4.1. Summary of findings

The aim of this systematic review was to investigate the relaxing effects of virtual interventions using HRV as marker for PNS activity. 18 studies were included in this review. Overall, the studies found a positive effect of virtual relaxation interventions on HRV as shown by various HRV markers, indicating an increase in relaxation (specifically, an increase in HF, pNN50, and RMSSD), in all three subgroups (with and without interaction and with biofeedback). The only study not reporting an effect on HRV markers used a biofeedback mini-game presented on a smartphone screen. The only study to directly compare different interaction possibilities found a stronger increase in parasympathetic activity (increase in SDSD) in reaction to a virtual environment when interaction was possible compared to the same environment without. This difference can potentially be explained by the notion that interaction with virtual environments is more effortlessly capturing the attention of participants and therefore more easily enables relaxation. In contrast, without the option to interact, participants need to focus on one environment for 9 min, which might require more voluntary attention to stop ruminating, therefore limiting the relaxing effects. On the other hand, interaction was shown to not always be superior to simply watching a virtual environment. Too complex interaction possibilities, like difficult mini-games, could thus have an arousing effect as well, demanding attention or even inducing tension.

The studies included in this review used either HMDs or screens to present the virtual environments. Of the 18 included studies the majority used a screen (computer or smartphone), probably because screens are less costly and used more frequently in daily life than HMDs. While there were significant effects of screen-based interventions on HRV, one study compared a screen directly with an HMD. This study found a significantly greater increase in parasympathetic activity (as indicated by an increase in SDSD) in reaction to the HMD based video, compared to the screen version. This was also associated with a greater sense of presence evoked by the HMD, indicating that being present in a virtual environment increases the positive effects the environment has on relaxation. HMDs are not as expensive or difficult to operate as they used to be when the technology first came out, thus making them a feasible relaxation intervention for many study groups nowadays.

Most studies included some form of self-report measurement, like PANAS or STAI. For most studies, results suggest that self-report measures changed in line with HRV measurements, for example, an increase in parasympathetic activity (HF) was associated with a decrease in reported anxiety (STAI). However, this relationship was not always seen, for example, one study (Parnandi & Gutierrez-Osuna, 2017) showed an increase in self-reported relaxation but no significant changes in HRV. This indicates, that there might be some differences between physiological and psychological relaxation, perhaps depending on the study design, or the population sample. This "dissociation" of subjective and objective measures has also been reported in stress research (Campbell & Ehlert, 2012; Dickerson & Kemeny, 2004) and thus seems to be generalizable across different psychophysiological states. It seems therefore good advice to always assess both when implementing a relaxation intervention.

Considering the different questionnaires used, the majority of studies did not assess relaxation directly (e.g., via a visual analog scale) but used other questionnaires, for example, asking subjects about anxiety or mood changes. Accordingly, a decrease in anxiety and negative affect and an increase in positive affect were interpreted as an increase in relaxation. Even though relaxation is associated with those changes in affect, it is unclear if they assess relaxation adequately and completely, since relaxation is likely more than a decrease in anxiety.

The virtual interventions implemented in the studies selected for this review used mostly nature stimuli (pictures, videos) to induce relaxation. Since all studies using nature stimuli reported a successful increase in parasympathetic activity, a successful transfer of the relaxing effects of real-life nature (for example Kobayashi et al., 2018; Payne & Delphinus, 2019; Song et al., 2018) to virtual adaptions of nature appears likely.

Even though all except one of the included studies found an increase in physiological relaxation it is important to differentiate between studies using a stressor preceding the virtual relaxation intervention and studies without a stressor. Seven studies employed a stressor before the relaxation intervention (Anderson et al., 2017; Byun et al., 2019; Gaggioli et al., 2020; Kim and Jeon, 2021, 2021, Liszio et al., 2018; Parnandi & Gutierrez-Osuna, 2015, 2017), therefore it is possible that the measured increase in relaxation is influenced by the rebound effect after a stressor in addition to the relaxing effects of the according interventions. The rebound effect after a stressor describes an increase in HRV in a recovery phase above the baseline level, especially in the first minute after the stressor (Mezzacappa et al., 2001). Adding a stressor makes it impossible to differentiate those two effects and therefore to assess the success of an intervention. Even though more research is needed to differentiate an increase in relaxation due to a rebound effect from an effect of an intervention, first results suggest that virtual environments exceed the rebound effect and lead to a faster recovery after a stressor. After a virtual Trier Social Stress Test participants recovered either in a virtual forest with sound, in a virtual forest without sound, or in a room without a virtual environment. HRV (HF) significantly increased only in the group sitting in a virtual forest with sounds during recovery period, while there were no significant changes in HRV in the other two groups (Annerstedt et al., 2013). This hints at an effect of virtual environments beyond a rebound effect after a stressor. Still, the differences between an increased recovery after a stressor and an increase in relaxation due to an intervention starting from baseline need to be differentiated and studied further. It is possible that relaxation interventions as used in the included studies positively affect the recovery after a stressor and therefore lead to a significant increase in relaxation compared to the stressor and a recovery group without intervention. It is also possible that the same interventions show no effect when used without a stressor because of ceiling effects (Guyon et al., 2020) and the missing influence of a rebound effect after a stressor. However, future studies are needed to shed more light on this matter.

4.2. Strengths and limitations of included studies

All studies together assessed a total of n = 816 (n = 414 (50.74%) female) participants. Seven studies did not meet the criteria of at least 20 participants per cell, 11 did not use a within-subjects design and only three assessed an appropriate baseline, which are all methodological recommendations for the assessment of HRV as recommended by Quintana and Heathers (2014). Within-subjects experiments do however risk carry-over effects and fatigue. To minimize these risks, some studies assessed the different conditions on separate days, leading to greater expense for both, experimenter and participants, and increased the risk for dropout due to participants' attrition across study appointments. Despite the difficulties associated with within-subject designs, they have multiple advantages. Fewer participants are needed in total to meet the 20 participants per cell criterion, potentially facilitating recruitment. Since every subject is serving as their own control, unsystematic variation is reduced, This is especially an advantage when measuring HRV. HRV is influenced by multiple within-subject factors, for example, disease, age, sex (Acharya et al., 2006), body-mass-index, or menstrual cycle (Vallejo et al., 2005), to name just a few. Choosing an appropriate baseline is an important part of the experimental design since it is needed to allow drawing conclusions about the changes in HRV induced by an intervention. The baseline should be comparable to the intervention (e.g., if the intervention is done with eyes open so should the baseline) and instructions given should be described (Laborde et al., 2017; Quintana et al., 2016; Quintana & Heathers, 2014). Of the included studies only three followed those recommendations (Anderson et al., 2017; Byun et al., 2019; Tonacci et al., 2020), eight assessed a baseline not following these recommendations (e.g., using a questionnaire assessment as baseline, e.g., Liszio & Masuch, 2019) and five did not assess a baseline at all. Most studies used a sample of young adults (approx. 20–30 years), with only one study using older participants (60–70 years), and no study assessed children. This limits the generalizability of results, as the very young, middle-aged, and older subjects are so far missing from or underrepresented in this type of investigation.

Across studies, a great diversity of the type of implemented HRV markers could be observed. Only one study used entropy measurements, all others used time and/or frequency domain measurements. This makes it difficult to compare results across the different studies adequately since different measurements are influenced by different factors. When looking at the physiological component of relaxation an increase in parasympathetic activity is expected, therefore studies should focus on the markers that are associated with PNS activity. Most prominently is high-frequency HRV, which is only influenced by the PNS (Berntson et al., 1993b). Since breathing has a huge impact on HF it is useful to assess other markers as well, for example, RMSSD or pNN50. Even though there is a small sympathetic influence in both of those markers they correlate highly with HF, indicating a dominant parasympathetic influence, and are not as strongly affected by breathing as HF (Laborde et al., 2017).

Special care is also needed when interpreting the HRV indices more strongly associated with sympathetic activity or a mix between parasympathetic and sympathetic activity (LF and LF/HF). Often a decrease of those markers and therefore sympathetic activity is interpreted as an increase in relaxation. This leads to the misconception that a decrease in sympathetic activity is always associated with an increase in parasympathetic activity and the other way around. The interactions between the two branches of the autonomic nervous system are complex and not that easy to interpret, since an increase in one can also lead to an increase in the other (Levy, 1971). They can exert opposing or synergetic effects and can vary in activity reciprocally, independently, or coactively (see Autonomic Space Model, Berntson et al., 1993b). Therefore, it is recommended to assess parasympathetic activity, using multiple markers (e.g., HF as frequency domain measurement and RMSSD as time domain measurement), since there are different factors influencing them, and not infer PNS activity from sympathetic activity, as this leads to wrong conclusions. When assessing HRV it is important to follow guidelines for the report of HRV measures (e.g., Quintana et al., 2016) and their interpretation. To enable the comparison of different studies it is strongly recommended that future studies follow those guidelines and report multiple markers strongly influenced by the PNS when physical relaxation is among the outcomes of interest.

An additional difficulty when using HRV as an outcome measurement are the various confounding factors influencing HRV. It is impossible to assess all of them, still, researchers should aim to give a comprehensive sample description including possible influencing factors, for example, age, sex, physical and psychological health (Acharya et al., 2006; Quintana & Heathers, 2014; Shaffer & Ginsberg, 2017), menstrual cycle (Vallejo et al., 2005) but also nicotine and caffeine intake before the experiment (Quintana & Heathers, 2014). Looking at the studies included in this systematic review shows a considerable lack of information about and consideration of possible influencing factors. Some studies reported assessing only healthy participants (e.g., Tonacci et al., 2020), or matching groups in age and sex (e.g., Rockstroh et al., 2019) but most studies did not take any influencing factors into account. This is another factor that complicates the interpretation of results.

4.3. Strengths and limitations of this review

A protocol for this systematic review was preregistered to make retracing the review process possible. The risk of bias rating for individual studies was done by two researchers independently, to reduce the possibility of bias.

The main limitation of this systematic review is the heterogeneity between included studies. This heterogeneity most clearly reveals itself when looking at the employed HRV indices, where studies used varying HRV markers as measurement for parasympathetic activity. The heterogeneity can also be seen when looking at the different interventions used to induce relaxation. Most studies used nature pictures, but some studies used mini-games, and therefore differ substantially from each other. The duration of exposure to virtual relaxation environments differed significantly, ranging from 90 s to 30 min across studies. It is not clear whether a longer exposure will always lead to stronger effects, as boredom and limited attention span will likely mean that there is an upper limit for the PNS stimulating effects. However, we are not aware of studies that have systematically investigated the effects of different time intervals on HRV markers in the context of relaxation. Additionally, the concepts of relaxation itself differed between studies, for example, not all studies defined a decrease in anxiety as an increase in relaxation. Finding a universally valid definition of relaxation is not an easy task. At a minimum, relaxation can be defined as a decrease of arousal on a physiological level (Smith, 2007), but this definition fails to include changes on an affective level, which are likely also an integral part of relaxation, to allow differentiating it, for example, from fatigue. Other studies include physiological as well as psychological measurements for relaxation (e.g., Knaust et al., 2022). Even though they not always correlate (e.g., Hernandez-Ruiz et al., 2020) both are needed to assess the relaxation on various levels. Since studies rarely define their concept of relaxation explicitly, this is an important point in which the studies differ from one another.

Since all except one study found a significant effect of their respective relaxation interventions on HRV indices this raises the question whether a publication bias played a role here. Since we did not deploy meta-analytic statistics we cannot answer this question based on statistical results. Nevertheless it seems unlikely that about 94% of all studies investigating the relaxation response using virtual interventions and measuring HRV found a significant effect, especially since HRV values are easily biased by external (e.g., room temperature) or internal (e.g., menstrual cycle) factors and ceiling effects are a known problem when assessing relaxation. It appears more likely that other similar studies not finding a significant effect simply were not published. This is a common problem, especially in psychology (Ferguson & Heene, 2012) adversely affecting the ability to reject theories. Thus, as a note of caution, readers should keep in mind that likely there are unpublished studies without a significant effect of virtual relaxation interventions on

HRV. Publishing those in the future would be a considerable contribution in search for a successful standardized relaxation protocol. Nevertheless we can only base future research on studies that were published, deriving characteristics of a successful relaxation intervention from the results of this systematic review.

4.4. Considerations of previous research

To our knowledge there is no review article describing different relaxation interventions and their effects on mental and physical health dependent on specifics of the intervention. Instead there are many different articles, focusing for example on a certain type of intervention (as we did with this systematic review) or on a certain type of participants (e.g., patients with depression). Nevertheless a previous systematic review (Jo et al., 2019) found positive effects on physiological parameters when viewing pictures of nature and additionally suggests an increased positive effect associated with a more realistic presentation of virtual nature environments, aligning with our findings. The article also mentions influences of interindividual differences like personality traits on the relaxation reaction, alongside considerations of other potentially influencing factors like mental diseases and the need for future research into this question. Since various physiological parameters including HRV were taken into account this hints that an increase in physiological relaxation in reaction to nature stimuli is not specific for HRV but instead a general physiological relaxation reaction. The success of virtual interventions to induce mental and physical relaxation was found to vary with the details of the experimental intervention (Diniz, Bernardo et al., 2021). Even though the authors did not specify this finding, it highlights the importance of taking a closer look at the details of an intervention. Additionally this review found that most studies assessed college students, emphasizing the need for studies with more diverse samples. Virtual nature stimuli are not only used in research settings, but as well in treatments for patients with mental disorders. First results are promising, showing increased mental and physical relaxation and even a greater effect of virtual reality based nature interventions compared to non-virtual interventions (e.g., guided meditation) (Riches et al., 2023). Similar results were found for healthy participants (Riches et al., 2021). Additionally a positive effect of 360° nature videos on depressive and anxiety symptoms was found (Ionescu et al., 2021). While these reviews emphasize the success of virtual nature environments as relaxation interventions for healthy participants and clinical samples, they all considered different physiological measures as well as self-report measures without distinguishing between mental and physical relaxation as separate aspects of the relaxation process, as we did in this systematic review. They also did not try to determine how the details of a successful relaxation intervention should look like. This might be due to the wide variety of measurements used in the included study. As in our review, others also described a significant heterogeneity in the characteristics of virtual relaxation intervention as well as little diversity regarding age and ethnicity of the study samples. Heterogeneity in measurements and interventions seems to be a general problem in the field of relaxation interventions, making it excessively difficult for this field of research to generalize findings across different studies and come to firm conclusions. This emphasizes the need for a standardized relaxation protocol, which would allow an in-depth investigation of the mechanisms behind the relaxation response as well as researching possible factors influencing relaxation and options to incorporate relaxation interventions into treatment plans.

4.5. Implications for future work

Despite the fundamental differences across the reported studies, all expect one found a significant increase in physiological relaxation as measured by HRV in reaction to the virtual interventions. These results suggest that virtual relaxation interventions could become an integral part of a standardized relaxation protocol to investigate the specifics of the relaxation response and its contribution to health and disease. Relaxation is a central aspect of a healthy lifestyle and part of many treatments in the context of psychopathology, thus making an in-depth understanding of the relaxation response and its effects crucial. First studies already show the influence of depression (Matsui et al., 2016) and interindividual differences on physiological relaxation (Benz et al., 2022), indicating that more research is needed to explore the various influences on the relaxation response. One aim of this study was to investigate whether virtual interventions could be part of a standardized relaxation protocol and which characteristics should be included in a successful relaxation intervention based on virtual environments. Since the main difficulty of this systematic review was the huge variety in relaxation interventions and measurements we summarized what a successful relaxation intervention should look like based on the findings. The majority of studies we included used virtual nature stimuli and found them to be effective in inducing relaxation, therefore this seems a promising start to developing a standardized relaxation intervention. Apparently, the greatest effects on physiological relaxation were observed in studies that achieved a high feeling of presence induced by the virtual intervention. This can be implemented, for example, by using HMD as presentation method or by adding means to interact with the virtual environment. Concerning the length of the intervention we found no hint at a systematic effect in the included studies, even though the interventions ranged from 90 s to 30 min. Here, more research is needed to determine what the optimal length for a relaxation intervention is. Of importance for a standardized relaxation protocol are not only the specifics of the intervention but also how relaxation is measured. All protocols interested in studying the parasympathetic branch of the autonomic nervous system should be aware of the different HRV indices and report both time and frequency domain measures. When using HRV as many different influencing factors as feasible should be assessed and reported, as well as adherence to the guidelines for HRV measurements (at least 20 participants per cell, within-subject design, adequate baseline, keep influence of SNS and PNS in mind when interpreting markers). Studies investigating specifically the relaxation response should make sure to include their definition of relaxation, to make comparison across studies easier. To assess the psychological aspects of relaxation in addition to the physiological ones, self-report questionnaires should always be used as well. Future projects should consider these aspects regardless of whether the aim is to develop a new protocol or implement a virtual relaxation method in the context of a clinical intervention.

4.6. Conclusion

This systematic review investigated whether virtual relaxation interventions can successfully increase relaxation measured by HRV. Despite significant heterogeneity across studies, results showed, that virtual interventions are promising relaxation interventions, especially when using nature stimuli and increasing the sense of presence. Future studies should aim to implement a standardized relaxation protocol using virtual interventions, to be able to investigate open questions concerning the relaxation response and its impact on health and disease. To accomplish this task a universal definition of relaxation and guidelines for its measurement are crucial to enable comparison and synthesis of different studies. Guidelines for relaxation measurement should include measuring psychological as well as physiological markers. When using HRV the guidelines for its measurement should be followed. If we work on this together, we are sure this will push the field of relaxation research considerably ahead, so that future research can work with a standardized virtual intervention and insights thus gained can improve not only therapeutic interventions but also everyday life.

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CRediT author statement

RJG: Conceptualization, Methodology, Data Curation, Investigation, Formal analysis, Visualization, Writing - Original Draft & Editing. KEK: Formal analysis, Writing - Review & Editing. ABEB, UUB, MM, BFD, SJD: Writing - Review & Editing. JCP: Formal analysis, Resources, Writing - Original Draft, Supervision, Conceptualization, Methodology. All authors approved the final version.

Declaration of competing interest

The authors declare no conflict of interest.

References

Acharya, R. U., Paul Joseph, K., Kannathal, N., Lim, C. M., & Suri, J. S. (2006). Heart rate variability: A review. *Medical, & Biological Engineering & Computing, 44*, 1031–1051.

Anderson, A. P., Mayer, M. D., Fellows, A. M., Cowan, D. R., Hegel, M. T., & Buckey, J. C. (2017). Relaxation with immersive natural scenes presented using virtual reality. *Aerosp. Med. Hum. Perform., 88*, 520–526.

Annerstedt, M., Jönsson, P., Wallergård, M., Johansson, G., Karlson, B., Grahn, P., Hansen, Å. M., & Währborg, P. (2013). Inducing physiological stress recovery with sounds of nature in a virtual reality forest—results from a pilot study. *Physiology and Behavior, 118*, 240–250.

de Back, T. T., Tinga, A. M., Nguyen, P., & Louwerse, M. M. (2020). Benefits of immersive collaborative learning in CAVE-based virtual reality. *Int. J. Educ. Technol. High. Educ., 17*, 1–18.

Bansal, D., Khan, M., & Salhan, A. K. (2009). A review of measurement and analysis of heart rate variability. In *2009 international conference on computer and automation engineering* (pp. 243–246). IEEE.

Benz, A. B., Gaertner, R. J., Meier, M., Unternaehrer, E., Scharndke, S., Jupe, C., Wenzel, M., Bentele, U. U., Dimitroff, S. J., & Denk, B. F. (2022). Nature-based relaxation videos and their effect on heart rate variability. *Frontiers in Psychology, 13*.

Berntson, G. G., Cacioppo, J. T., & Quigley, K. S. (1993a). Cardiac psychophysiology and autonomic space in humans: Empirical perspectives and conceptual implications. *Psychological Bulletin, 114*, 296.

Berntson, G. G., Cacioppo, J. T., & Quigley, K. S. (1993b). Respiratory sinus arrhythmia: Autonomic origins, physiological mechanisms, and psychophysiological implications. *Psychophysiology, 30*, 183–196.

Bertsch, K., Hagemann, D., Naumann, E., Schaechinger, H., & Schulz, A. (2012). Stability of heart rate variability indices reflecting parasympathetic activity. *Psychophysiology, 49*, 672–682.

Bhasin, M. K., Dusek, J. A., Chang, B.-H., Joseph, M. G., Denninger, J. W., Fricchione, G. L., Benson, H., & Libermann, T. A. (2013). Relaxation response induces temporal transcriptome changes in energy metabolism, insulin secretion and inflammatory pathways. *PLoS One, 8*, Article e62817.

Billman, G. E. (2011). Heart rate variability–a historical perspective. *Frontiers in Physiology, 2*, 86.

Billman, G. E. (2013). The LF/HF ratio does not accurately measure cardiac sympatho-vagal balance. *Frontiers in Physiology*.

Brajša-Žganec, A., Ivanović, D., & Kaliterna Lipovčan, L. (2011). Personality traits and social desirability as predictors of subjective well-being. *Psihologijske teme, 20*(2), 261–276.

Bravo, A. J., Pearson, M. R., Wilson, A. D., & Witkiewitz, K. (2018). When traits match states: Examining the associations between self-report trait and state mindfulness following a state mindfulness induction. *Mindfulness, 9*, 199–211.

Byun, S., Kim, A. Y., Jang, E. H., Kim, S., Choi, K. W., Yu, H. Y., & Jeon, H. J. (2019). Entropy analysis of heart rate variability and its application to recognize major depressive disorder: A pilot study. *Technology and Health Care, 27*, 407–424.

Campbell, J., & Ehlert, U. (2012). Acute psychosocial stress: Does the emotional stress response correspond with physiological responses? *Psychoneuroendocrinology, 37*, 1111–1134.

Choi, K.-H., Kim, J., Kwon, O. S., Kim, M. J., Ryu, Y. H., & Park, J.-E. (2017). Is heart rate variability (HRV) an adequate tool for evaluating human emotions?–A focus on the use of the International Affective Picture System (IAPS). *Psychiatry Research, 251*, 192–196.

Dickerson, S. S., & Kemeny, M. E. (2004). Acute stressors and cortisol responses: A theoretical integration and synthesis of laboratory research. *Psychological Bulletin, 130*, 355.

Diniz Bernardo, P., Bains, A., Westwood, S., & Mograbi, D. C. (2021). Mood induction using virtual reality: A systematic review of recent findings. *Journal of Technology in Behavioral Science, 6*, 3–24.

Dua, S., Du, X., Sree, S. V., & VI, T. A. (2012). Novel classification of coronary artery disease using heart rate variability analysis. *Journal of Mechanics in Medicine and Biology, 12*, Article 1240017.

Electrophysiology, T.F. of the E.S. of C. the N.A.S. of P.. (1996). Heart rate variability: Standards of measurement, physiological interpretation, and clinical use. *Circulation, 93*, 1043–1065.

Engel, J. M., Rapoff, M. A., & Pressman, A. R. (1992). Long-term follow-up of relaxation training for pediatric headache disorders. *Headache: The Journal of Head and Face Pain, 32*, 152–156.

Farrow, M. R., & Washburn, K. (2019). A review of field experiments on the effect of forest bathing on anxiety and heart rate variability. *Global Advances in Health and Medicine, 8*, Article 2164956119848654.

Ferguson, C. J., & Heene, M. (2012). A vast graveyard of undead theories: Publication bias and psychological science's aversion to the null. *Perspectives on Psychological Science, 7*(6), 555–561.

Fisher, R. J., & Katz, J. E. (2000). Social-desirability bias and the validity of self-reported values. *Psychology and Marketing, 17*(2), 105–120.

Francesco, B., Maria Grazia, B., Emanuele, G., Valentina, F., Sara, C., Chiara, F., Riccardo, M., & Francesco, F. (2012). Linear and nonlinear heart rate variability indexes in clinical practice. *Computational and Mathematical Methods in Medicine*, 2012.

Gaggioli, A., Gianotti, E., & Chirico, A. (2020). Psycho-physiological effects of a virtual reality relaxation experience after acute stressor exposure. *Annu. Rev. CYBERTHERAPY TELEMEDICINE, 123*, 2020.

Gladwell, V. F., Brown, D. K., Barton, J. L., Tarvainen, M. P., Kuoppa, P., Pretty, J., Suddaby, J. M., & Sandercock, G. R. H. (2012). The effects of views of nature on autonomic control. *European Journal of Applied Physiology, 112*, 3379–3386.

Guyon, A., Aridhi, S., Iranfar, S., & Gomes, N. (2020). Physiological and psychological effects of rapid relaxation devices using sensorial immersion: A pilot study. *J. Interdiscip. Methodol. Issues Sci.*

Hernandez-Ruiz, E., James, B., Noll, J., & Chrysikou, E. G. (2020). What makes music relaxing? An investigation into musical elements. *Psychology of Music, 48*, 327–343.

Higgins, J. P., Savović, J., Page, M. J., Elbers, R. G., & Sterne, J. A. (2019). Assessing risk of bias in a randomized trial. *Cochrane Handb. Syst. Rev. Interv.*, 205–228.

Huang, C.-Y., Hsieh, Y.-M., & Lai, H.-L. (2016). Effect of stimulative and sedative music videos on depressive symptoms and physiological relaxation in older adults: A pilot study. *Research in Gerontological Nursing, 9*, 233–242.

Igarashi, M., Yamamoto, T., Lee, J., Song, C., Ikei, H., & Miyazaki, Y. (2014). Effects of stimulation by three-dimensional natural images on prefrontal cortex and autonomic nerve activity: A comparison with stimulation using two-dimensional images. *Cognitive Processing, 15*, 551–556.

Ionescu, A., Van Daele, T., Rizzo, A., Blair, C., & Best, P. (2021). 360 videos for immersive mental health interventions: A systematic review. *Journal of Technology in Behavioral Science, 6*(4), 631–651.

Jo, H., Song, C., & Miyazaki, Y. (2019). Physiological benefits of viewing nature: A systematic review of indoor experiments. *International Journal of Environmental Research and Public Health, 16*(23), 4739.

Kim, H.-G., Cheon, E.-J., Bai, D.-S., Lee, Y. H., & Koo, B.-H. (2018). Stress and heart rate variability: A meta-analysis and review of the literature. *Psychiatry Investig, 15*, 235.

Kim, H., & Jeon, H. J. (2021). Predicting who will benefit from relaxation or stress reduction through virtual reality. In *2021 15th international conference on ubiquitous information management and communication (IMCOM)* (pp. 1–5). IEEE.

Kim, H., Kim, D. J., Kim, S., Chung, W. H., Park, K.-A., Kim, J. D., Kim, D., Kim, M. J., Kim, K., & Jeon, H. J. (2021). Effect of virtual reality on stress reduction and change of physiological parameters including heart rate variability in people with high stress: An open randomized crossover trial. *Frontiers in Psychiatry, 12*.

Klainin-Yobas, P., Oo, W. N., Suzanne Yew, P. Y., & Lau, Y. (2015). Effects of relaxation interventions on depression and anxiety among older adults: A systematic review. *Aging & Mental Health, 19*, 1043–1055.

Kleiger, R. E., Stein, P. K., & Bigger, J. T., Jr. (2005). Heart rate variability: Measurement and clinical utility. *Annals of Noninvasive Electrocardiology, 10*, 88–101.

Knaust, T., Felnhofer, A., Kothgassner, O. D., Hoellmer, H., Gorzka, R.-J., & Schulz, H. (2022). Exposure to virtual nature: The impact of different immersion levels on skin conductance level, heart rate, and perceived relaxation. *Virtual Reality, 26*, 925–938.

Knowles, K. A., & Olatunji, B. O. (2020). Specificity of trait anxiety in anxiety and depression: Meta-analysis of the state-trait anxiety inventory. *Clinical Psychology Review, 82*, Article 101928.

Kobayashi, H., Song, C., Ikei, H., Park, B.-J., Lee, J., Kagawa, T., & Miyazaki, Y. (2018). Forest walking affects autonomic nervous activity: A population-based study. *Frontiers in Public Health, 278*.

Kohl, C., McIntosh, E. J., Unger, S., Haddaway, N. R., Kecke, S., Schiemann, J., & Wilhelm, R. (2018). Online tools supporting the conduct and reporting of systematic reviews and systematic maps: A case study on CADIMA and review of existing tools. *Environmental Evidence, 7*, 1–17.

Laborde, S., Mosley, E., & Thayer, J. F. (2017). Heart rate variability and cardiac vagal tone in psychophysiological research–recommendations for experiment planning, data analysis, and data reporting. *Frontiers in Psychology, 8*, 213.

Lee, H. B., Chiu, H. F., Kowk, W. Y., & Leung, C. M. (1993). Chinese elderly and the GDS short form: A preliminary study. *Clin. Gerontol. J. Aging Ment. Health.*

Levy, M. N. (1971). Brief reviews: Sympathetic-parasympathetic interactions in the heart. *Circulation Research, 29*, 437–445.

Liszio, S., Graf, L., & Masuch, M. (2018). The relaxing effect of virtual nature: Immersive technology provides relief in acute stress situations. *Annu Rev Cyberther Telemed, 16*, 87–93.

Liszio, S., & Masuch, M. (2019). Interactive immersive virtual environments cause relaxation and enhance resistance to acute stress. *Annu Rev Cyberther Telemed, 17*, 65–71.

Liu, C., Li, K., Zhao, L., Liu, F., Zheng, D., Liu, C., & Liu, S. (2013). Analysis of heart rate variability using fuzzy measure entropy. *Computers in Biology and Medicine, 43*, 100–108.

Matsui, T., Kakisaka, K., & Shinba, T. (2016). Impaired parasympathetic augmentation under relaxation in patients with depression as assessed by a novel non-contact microwave radar system. *Journal of Medical Engineering & Technology, 40*, 15–19.

McCorry, L. K. (2007). Physiology of the autonomic nervous system. *American Journal of Pharmaceutical Education, 71*.

McGuinness, L. A., & Higgins, J. P. T. (2021). Risk-of-bias VISualization (robvis): An R package and Shiny web app for visualizing risk-of-bias assessments. *Research Synthesis Methods, 12*, 55–61. https://doi.org/10.1002/jrsm.1411

McNair, D. M., Lorr, M., & Droppleman, L. F. (1981). *Profile of mood states*. Serv: San Diego Educ. Test. Ind. Test.

Meier, M., Unternaehrer, E., Dimitroff, S. J., Benz, A. B., Bentele, U. U., Schorpp, S. M., Wenzel, M., & Pruessner, J. C. (2020). Standardized massage interventions as protocols for the induction of psychophysiological relaxation in the laboratory: A block randomized, controlled trial. *Scientific Reports, 10*, 1–12.

Mezzacappa, E. S., Kelsey, R. M., Katkin, E. S., & Sloan, R. P. (2001). Vagal rebound and recovery from psychological stress. *Psychosomatic Medicine, 63*, 650–657.

Miglis, M. G. (2017). Sleep and the autonomic nervous system. In *Sleep and neurologic disease* (pp. 227–244). Elsevier.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., & Group, P. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *PLoS Medicine, 6*, Article e1000097.

Moher, D., Shamseer, L., Clarke, M., Ghersi, D., Liberati, A., Petticrew, M., Shekelle, P., & Stewart, L. A. (2015). Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. *Systematic Reviews, 4*, 1–9.

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., & Brennan, S. E. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *International Journal of Surgery, 88*, Article 105906.

Parnandi, A., & Gutierrez-Osuna, R. (2015). Physiological modalities for relaxation skill transfer in biofeedback games. *IEEE J. Biomed. Health Inform., 21*, 361–371.

Parnandi, A., & Gutierrez-Osuna, R. (2017). Visual biofeedback and game adaptation in relaxation skill transfer. *IEEE Trans. Affect. Comput., 10*, 276–289.

Payne, M. D., & Delphinus, E. (2019). A review of the current evidence for the health benefits derived from forest bathing. *The International Journal of Health, Wellness and Society, 9*.

Quintana, D. S., Alvares, G. A., & Heathers, J. A. J. (2016). Guidelines for reporting articles on psychiatry and heart rate variability (GRAPH): Recommendations to advance research communication. *Translational Psychiatry, 6*. e803–e803.

Quintana, D. S., & Heathers, J. A. (2014). Considerations in the assessment of heart rate variability in biobehavioral research. *Frontiers in Psychology, 5*, 805.

Rebenitsch, L., & Owen, C. (2016). Review on cybersickness in applications and visual displays. *Virtual Reality, 20*, 101–125.

Riches, S., Azevedo, L., Bird, L., Pisani, S., & Valmaggia, L. (2021). Virtual reality relaxation for the general population: A systematic review. *Social Psychiatry and Psychiatric Epidemiology, 56*, 1707–1727.

Riches, S., Jeyarajaguru, P., Taylor, L., Fialho, C., Little, J., Ahmed, L., … Valmaggia, L. (2023). Virtual reality relaxation for people with mental health conditions: A systematic review. *Social Psychiatry and Psychiatric Epidemiology*, 1–19.

Riva, G., Gaggioli, A., Pallavicini, F., Algeri, D., Gorini, A., & Repetto, C. (2010). Ubiquitous health for the treatment of generalized anxiety disorders. *UbiComp '10 Cph. Den.*

Rockstroh, C., Blum, J., & Göritz, A. S. (2019). Virtual reality in the application of heart rate variability biofeedback. *International Journal of Human-Computer Studies, 130*, 209–220.

Russoniello, C. V., O'Brien, K., & Parks, J. M. (2009a). EEG, hrv and psychological correlates while playing bejeweled II: A randomized controlled study. *Annu. Rev. Cybertherapy Telemed., 7*, 189–192.

Russoniello, C. V., O'Brien, K., & Parks, J. M. (2009b). The effectiveness of casual video games in improving mood and decreasing stress. *J. CyberTherapy Rehabil., 2*, 53–66.

Santarcangelo, E. L., Paoletti, G., Balocchi, R., Scattina, E., Ghelarducci, B., & Varanini, M. (2012). Watching neutral and threatening movies: Subjective experience and autonomic responses in subjects with different hypnotizability levels. *International Journal of Psychophysiology, 84*, 59–64.

Schubert, T., Friedmann, F., & Regenbrecht, H. (1999). Embodied presence in virtual environments. In *Visual representations and interpretations* (pp. 269–278). Springer.

Schwartz, M. S. (2010). A new improved universally accepted official definition of biofeedback: Where did it come from? Why? Who did it? Who is it for? What's next? *Biofeedback, 38*, 88–90.

Shaffer, F., & Ginsberg, J. P. (2017). An overview of heart rate variability metrics and norms. *Frontiers in Public Health, 258*.

Shaffer, F., & Venner, J. (2013). Heart rate variability anatomy and physiology. *Biofeedback Online, 41*, 13.

Smith, J. C. (2007). The new psychology of relaxation and renewal. *Biofeedback, 35*, 85–89.

Smith, C., Hancock, H., Blake-Mortimer, J., & Eckert, K. (2007). A randomised comparative trial of yoga and relaxation to reduce stress and anxiety. *Complementary Therapies in Medicine, 15*, 77–83.

Solberg, E. E., Ingjer, F., Holen, A., Sundgot-Borgen, J., Nilsson, S., & Holme, I. (2000). Stress reactivity to and recovery from a standardised exercise bout: A study of 31 runners practising relaxation techniques. *British Journal of Sports Medicine, 34*, 268–272.

Song, C., Ikei, H., Park, B.-J., Lee, J., Kagawa, T., & Miyazaki, Y. (2018). Psychological benefits of walking through forest areas. *International Journal of Environmental Research and Public Health, 15*, 2804.

Spielberger, C. D., Gonzalez-Reigosa, F., Martinez-Urrutia, A., Natalicio, L. F., & Natalicio, D. S. (1971). The state-trait anxiety inventory. *Rev. Interam. Psicol. J. Psychol., 5*.

Steghaus, S., & Poth, C. H. (2021). *Assessing momentary states of relaxation: The relaxation state questionnaire*.

Steyer, R., Schwenkmezger, P., Notz, P., & Eid, M. (1997). *Der mehrdimensionale befindlichkeitsfragebogen (MDBF). Handanweisung [the multidimensional mood questionnaire]*. Göttingen, Germany: Hogrefe.

Szulczewski, M. T. (2019). Training of paced breathing at 0.1 Hz improves CO2 homeostasis and relaxation during a paced breathing task. *PLoS One, 14*, Article e0218550.

Tonacci, A., Dellabate, A., Dieni, A., Bachi, L., Sansone, F., Conte, R., & Billeci, L. (2020). Can machine learning predict stress reduction based on wearable sensors' data following relaxation at workplace? *A Pilot Study. Processes, 8*, 448.

Tsutsumi, M., Nogaki, H., Shimizu, Y., Stone, T. E., & Kobayashi, T. (2017). Individual reactions to viewing preferred video representations of the natural environment: A comparison of mental and physical reactions. *Japan Journal of Nursing Science, 14*, 3–12.

Vallejo, M., Márquez, M. F., Borja-Aburto, V. H., Cárdenas, M., & Hermosillo, A. G. (2005). Age, body mass index, and menstrual cycle influence young women's heart rate variability. *Clinical Autonomic Research, 15*, 292–298.

Veling, W., Lestestuiver, B., Jongma, M., Hoenders, H. R., & van Driel, C. (2021). Virtual reality relaxation for patients with a psychiatric disorder: Crossover randomized controlled trial. *Journal of Medical Internet Research, 23*, Article e17233.

Voss, A., Schulz, S., Schroeder, R., Baumert, M., & Caminal, P. (2009). Methods derived from nonlinear dynamics for analysing heart rate variability. *Philos. Trans. R. Soc. Math. Phys. Eng. Sci., 367*, 277–296.

Watson, D., Clark, L. A., & Tellegen, A. (1988). Development and validation of brief measures of positive and negative affect: The PANAS scales. *Journal of Personality and Social Psychology, 54*, 1063.

Witmer, B. G., & Singer, M. J. (1998). Measuring presence in virtual environments: A presence questionnaire. *Presence, 7*, 225–240.

Yamamoto, K., & Nagata, S. (2011). Physiological and psychological evaluation of the wrapped warm footbath as a complementary nursing therapy to induce relaxation in hospitalized patients with incurable cancer: A pilot study. *Cancer Nursing, 34*, 185–192.