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A meta-analysis of physiological stress responses to natural environments: Biophilia and Stress Recovery Theory perspectives

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ABSTRACT

Several theories, including the Biophilia Hypothesis and Stress Recovery Theory, promote the positive effects of connection to nature on human health and well-being. This article builds on these theories by presenting the results of a meta-analysis of experimental studies on the effects of natural environments on physiological stress. Through a systematic review process, 47 articles were included in the analysis, with a combined sample size of 2430 participants. The overall findings of the study indicated that natural environments had a small to medium effect on reducing physiological stress, compared to equivalent exposure to urban environments. This finding broadly supported both Stress Recovery Theory and the Biophilia Hypothesis. However, subgroup analysis indicated that the stress state of participants was not related to the effect of natural environments in reducing human stress, which contradicts one of the foundations of Stress Recovery Theory. Similarly, uncertain results were obtained regarding type of exposure to environments (immersion, laboratory exposure, or virtual reality), the effects of natural environments on participants with health conditions, and sensitivity of particular outcome measures. The meta-analysis provided general evidence for the theoretical landscape, whilst raising questions as to certain aspects of the dominant theories and the experimental body of knowledge available to support them.

1. Background

1.1. Development of dominant theories

There are a number of theories which consider the connection between humans and nature, either exclusively or as part of a broader hypothesis. These theories were generally developed by the disciplines of ecopsychology (Hasbach & Kahn, 2012) and environmental psychology (Steg & de Groot, 2019).

The early study of human relationships to the environment was primarily developed through research in environmental preference and the environmental psychology cohort from the 1960s to the 1980s. However, a theoretical framework for a 160 article body of literature reviewed by Zube et al. (1982) was not apparent. Research had been conducted within four paradigms which were separate in the literature and which could not be reduced through any theoretical framework. These paradigms were identified by Zube et al. (1982) as expert, psychophysical, cognitive, and experiential. Similar research paradigms run through the research to the present day (Ives et al., 2017).

In response to the lack of theoretical underpinning, a number of theories were developed. The three dominant theories concerning the effects of human connection to nature are the Biophilia Hypothesis (Wilson, 1986), Stress Reduction Theory (SRT) (Ulrich et al., 1991), and Attention Restoration Theory (ART) (Kaplan & Kaplan, 1989). These theories provide a biological and psychological basis to the psychological and physiological effects of exposure to nature. It is noted that ART and sometimes SRT may be combined into an overarching theory of Restorative Environments (Han, 2001).

Biophilia, ART, and SRT underpin the outcomes of empirical research concerning the effects of natural environments on human emotion, attention and stress. These theories explore a predominantly psychological relationship between human and nature, with physiological effects such as the physical signs of stress a resultant outcome. To date, there has been a significant body of work exploring the psychological effects of nature on humans, consolidated in works such as Gaekwad et al. (2022), Gillis and Gatersleben (2015), Berto (2014) and Bowler et al. (2010). In terms of the dominant theories, discussed, SRT and the Biophilia Hypothesis are particularly relevant to the present work and are further discussed below.

Stress Recovery Theory is based on the proposition that the greatest

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benefit from viewing scenes of nature is when people are experiencing a state of elevated stress. This proposition was based on empirical data from Ulrich (1979, 1981) indicating that viewing natural scenes allowed people to reduce arousal faster and to a greater magnitude. The response framework of SRT explored in Ulrich (1983, 1986) also adopted the concept of affect preceding cognition (Zajonc, 1984). The framework is notable for accounting for the pre-exposure affective and arousal state and the influence of learned behaviours on cognition. The response framework of SRT therefore implies that while psychoevolutionary theory accounts for the pre-cognition affective reaction, culture and experience influences the post-cognitive state.

The term "biophilia" was first used by psychoanalyst Erich Fromm as "the passionate love of life and of all that is alive" (Fromm, 1973, p. 365). Wilson (1986, p. 1) used a more specific definition, the "innate tendency to focus on life and life-like processes". This focus on life is proposed to be a psychological and emotional connection that elicits complex behaviours (Kellert & Wilson, 1993).

The Biophilia Hypothesis has been grouped by Albrecht (2019) with a number of other theories under the umbrella term "psychoterratic typologies", a term encompassing the relationship between human psyche and the earth (terra). There are a number of both positive and negative psyche-earth affiliations considered under this term. The most notable positive affiliations include topophilia (emotional bond with place) (Sampson, 2012; Tuan, 1990), ecophilia (connection to ecosystem (Sobel, 1996);), and biophilia. Gaekwad et al. (2022) provide a more detailed review of the concept of biophilia, including it's biological basis and criticism of the hypothesis.

1.2. Stress

Selye (1973, p. 15) generally defined stress as "the nonspecific response of the body to any demand" made upon it. However, their is a lack of consensus on the definition of stress and its biomarkers presents an obstacle for researchers and clinicians (Kim et al., 2018). Thayer et al. (2012, p. 747) states "one (obstacle) is a lack of consensus on the meaning and operationalization of the concept of stress. Another is the lack of a comprehensive framework in which to investigate the way in which organisms function and adapt in a constantly changing environment". Noting these challenges and uncertainties, a brief discussion on stress and physiology is provided to contextualise this meta-analysis and its results.

The physiological response to stress may be described in terms of General Adaptation Syndrome and its consecutive stages of alarm, resistance, and exhaustion (Selye, 1936). Each of these stages represents the differing ability of the body to resist stress, which changes with time as the stressor is maintained. A perspective of allostatis has also been taken on stress, where physiological changes are used to respond to stressors or general stimulus (McEwen, 1998). This mechanism results in stress when a sufficient response to a perceived stressor is unavailable. The effects of stress have also been described in terms of homeostasis (Chrousos, 2009), however Koolhaas et al. (2011, p. 1292) presents criticism of the homeostasis perspective, stating "the definition of stress as a threat to homeostasis is almost meaningless".

Stress may be caused by a wide variety of non-specific demands including "mental, social, environmental, or physical demands" (McSweeney et al., 2021, p. 2). Further to Selye's (1973) definition of stress, he highlights that the human response is the same whether the stressor (the external stimulus) may be regarded as pleasant or unpleasant. This led to definitions of positive stress or eustress, and bad stress or distress (McEwen & Akil, 2020; Selye, 1973). Both eustress and distress evoke similar physiological responses but their effects on health and well-being are quite different.

The previously discussed frameworks have many similarities, yet differ in how they describe the stress response. The review of Berto (2014) on the role of nature on psycho-physiological outcomes uses three groups for these outcomes; physiological effects, behavioural effects, and self-report measures. In the context of the meta-analysis presented herein, the focus is on physiological effects of distress only.

The "fight or flight" response (McSweeney et al., 2021) is often discussed as a physiological manifestation of stress. This response results in a number of physiological effects, most notably the dominance of the sympathetic branch over the parasympathetic branch of the autonomic nervous system (Viamontes & Nemeroff, 2009). The varying physiological responses to stimuli are described in a simplified fashion by Arnetz and Ekman (2006). These effects form the basis of the physiological markers of stress and measurement of stress, as discussed in the next section.

1.3. Physiological measurement of stress

A wide range of physiological stress outcome measures were identified as part of the literature review. This section briefly discusses these outcome measures and how they are related to stress. Table 1 displays the expected direction of each measured physiological outcome variable given a reduction in stress. These responses can generally be classed in two groups. The primary group is related to the effect on the heart and lungs of activation of the sympathetic nervous system as part of the stress response. This includes a raised heart rate (Vrijkotte et al., 2000) and respiration rate (Masaoka & Homma, 1997), as well as decreased heart rate recovery time (Sonntag-Öström et al., 2014) and heart rate variability (Kim et al., 2018; Taelman et al., 2009). Changes to heart rate variability also include a reduction in the high frequency component of the signal and an increase in the derivative high frequency to low frequency ratio (Hjortskov et al., 2004). There are number of measured variables associated with heart rate variability, which each variable having its own response to sympathetic activation (i.e. either increasing, decreasing, or remaining unchanged). In a similar vein, both systolic and diastolic blood pressure increase with stress (Gasperin et al., 2009), peripheral oxygen saturation increases (Bryan, 1990), and cerebral oxygen saturation increases (Bryan, 1990) as the sympathetic nervous system exerts control over the major organs.

The other measured effects of the activation of the sympathetic nervous system include increased electrodermal activity (Critchley, 2002), increased salivary cortisol (Kanelli et al., 2021), and increased salivary alpha amylase (Nater and Rohleder, 2009). Elevated urinary

Table 1
Direction of each measured physiological outcome variable, given a reduction in stress.

Measured Outcome Variable	Direction for Reduced Stress
Blood Pressure	↓
Heart Rate	↓
HR recovery	↓
HRV HF	↑
HRV LF/HF	↓
HRV LF	↑
HRV RMSSD	↑
HRV NN50	↑
HRV TINN	↑
HRV RR	↑
EEG alpha	↑
EEG low beta	↓
EEG high beta	↓
EEG delta	↑
EEG theta	↑
Cerebral blood flow	↓
EDA	↓
Peripheral oxygen saturation	↓
Respiration rate	↓
Salivary cortisol	↓
Salivary alpha amylase	↓
Salivary testosterone	↓
Uninary adrenaline	↓
Urinary dopamine	↓
Urinary noradrenaline	↓

markers such as adrenaline (Li et al., 2011), noradrenaline (Li et al., 2011), and dopamine (Fibiger and Singer, 1984) are also observed as an effect of stress. Salivary testosterone is theorised to increase with stress, due to the link between elevated testosterone levels and social competition (Archer, 2006;Geniole et al., 2016), however this may not be an indicator of sympathetic nervous system activation.

Various electroencephalogram (EEG) signals also change with stress, however the links between power in each frequency band and the effects of stress are less clear than the direct physiological effects discussed above. Based on the available literature, it may be summarised that alpha, delta, and theta waves decrease with stress, and beta waves (low and high) increase with stress (Aspinall et al., 2015; Grassini et al., 2022; Reeves et al., 2019).

All outcome measures identified, with the possible exception of salivary testosterone, are related to activation of the sympathetic nervous system and corresponding effects on the body. It would be expected that many of these outcome measures would correlate, as they are measuring the same physiological response through a variety of different indicators. Although not regarded as a simple one-dimensional continuum between parasympathetic and sympathetic dominance of the autonomic nervous system (Berntson et al., 1994), a change in the discussed variables is likely to indicate an increase or decrease in sympathetic nervous system activity. It may therefore be inferred that a change in the physiological stress state of a participant has occurred. Overall, this family of physiologically measured outcome variables for stress form the basis of the statistical analysis of this meta-analysis.

1.4. Previous work

Several recent reviews have been conducted which are related to the present work. The most relevant is Yao et al. (2021), which reports the results of a meta-analysis on the effect of exposure to the natural environment on stress. This study considers both physiological and psychological self-report measures of stress, and excludes non-immersion exposure to environments. 31 studies were found, with a total of 1842 participants. Positive effects of the natural environment in reducing stress were identified.

Two systematic reviews of the effects of the natural environment on stress were also recently conducted. Corazon et al. (2019) considers physiological effects as a specific primary research question, but also considers immersion in environments only. One of the conclusions of this article is that physiological effects reported in the literature are ambiguous. The present work builds on this in an effort to reduce the ambiguity in the literature. Kondo et al. (2018) conducted a systematic review with the primary research question being related to the measurement of stress, not necessarily the outcomes of exposure to the natural environment on stress. The authors conclude that physiological outcome measures of heart rate and blood pressure (along with self-report measures) "provide the most convincing support for the hypothesis that spending time in outdoor environments reduces the experience of stress" (Kondo et al., 2018, p. 148).

Antonelli et al. (2019) and Song et al. (2016) both reviewed the physiological effects of nature therapy and shinrin-yoku (forest bathing), a particular type of nature exposure known in Japan. Antonelli et al. (2019) included studies predominantly from Japan and considered only salivary cortisol as a bio-marker of stress and outcome variable. The meta-analysis indicated inconclusive results with reduced salivary cortisol in the nature condition both before and after the exposure. Song et al. (2016) conducted a systematic review of studies in Japan only, but could not derive any clear conclusions from the gathered evidence.

As noted above and in Section 1.1, the present work addresses a current gap in knowledge by broadening inclusion criteria to include laboratory and virtual reality exposure to environments, and seeking to summarise physiological effects.

2. Objectives

The meta-analysis targeted a single primary objective, and several secondary objectives. The primary objective, presented in a population, exposure, comparison, outcome (PECO) (Morgan et al., 2018) format was, "In adults, is immersive, virtual reality, or laboratory exposure to natural environments effective, compared to equivalent exposure to urban environments, in decreasing physiological stress?". The components of this primary objective were used to formulate the search terms and inclusion criteria of the literature search, as discussed in Section 3.2.

Four secondary objectives were also targeted by the analysis. The secondary objectives were.

- Do participants with specific stress-related health conditions experience a different outcome from exposure to nature compared to the general population?
- Is immersion in environments more effective in reducing stress compared to simulation of environments?
- Are there particular experimental methods which demonstrate consistently increased sensitivity to displaying the effects of natural and urban environments on stress?

The secondary objectives influenced the metadata extraction from the included articles. It was anticipated that all secondary objectives could be achieved through subgroup analysis of the extracted data set.

3. Methods

3.1. General

The reporting requirements of the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) (Moher et al., 2009) were used when conducting the review and analysis, and preparing this article. The review protocol was also registered on PROSPERO (Reference: CRD42022378285), an online database of systematic review protocols. Registration of the review occurred early in the screening stage. Registration of the review was considered key to a transparent review process and to inform the academic body as to the progress of the review to avoid replication of work.

3.2. Inclusion criteria

The inclusion criteria were directly developed from the PECO (Morgan et al., 2018) format of the primary research objective. Detailed inclusion criteria for this meta-analysis, presented using the PECO structure, were as follows.

- Population: Adults (over 18 years of age). Participants who may have a specific health condition were included in the study. Any health conditions must have not impacted the ability of participants to participate in the study (e.g. visual impairment, etc. were excluded).
- Type of exposure: Immersive, virtual reality, or laboratory simulation of outdoor environments. Simulation of environments must have been visual at a minimum, but may also have included other sensory components (e.g. olfactory). The term "virtual reality" is considered to cover high-quality real-time, 3D simulation of environments using immersive environment technology, as opposed to laboratory simulation, which may include viewing a photo slideshow or videos on a computer monitor or television. Participants must have undertaken equivalent activities for both the nature and urban exposure (e.g. physical activity). Articles considering biophilic interior design (i.e. design of indoor spaces which include elements of nature) were not included.
- Intervention and comparator: The intervention and comparator must have been equivalent exposure to natural and urban environments. The environments used in the study must have been discussed, and

cannot have been inferred from other variables (such as leaf area index from satellite imagery). Studies which did not directly control the type of environment and exposure were excluded.

- Outcome: Physiological outcomes related to stress must have been measured.
- Article type: Peer reviewed experimental studies with exposure to both natural and urban environments. Articles must have been published in English. Book chapters were excluded. Conference papers, Masters theses, and PhD theses were included. Reviews were marked for incorporation into backward snowballing following title, abstract, and full-text screening. No date limiters were applied.
- Study design: Within- or between-subjects randomised experimental trials which tested for environment (nature, urban) as an independent variable.

3.3. Literature search

The literature search consisted of a search of online databases. The search was conducted in November 2022. A search string was developed from the syntax of the primary objective. This string was then converted into the appropriate syntax for the search tools for each database. While an equivalent search string for each database was targeted, in some instances an exact match between search types could not be achieved between databases. The search strings are presented in Appendix A.

The literature search was directed at seven databases selected for both breadth and relevance to the primary disciplines under which this literature search was expected to fall (psychology, environmental psychology, and health). Large, general databases were also included for further breadth. The searched databases were Web of Science Core Collection, Scopus, Embase, Medline, CINAHL Complete, PsycINFO, and Global Health. The Web of Science platform was used to search both the Web of Science Core Collection and Medline. The EBSCOhost platform was used to search PsycINFO, Global Health, and CINAHL Complete. The database literature search identified a total of 1792 articles.

The literature search strategy also included both backward and forward snowballing of certain articles. Backwards snowballing was conducted on review articles which were not excluded during the title, abstract, and full-text screening process. Forward snowballing was conducted for all articles which reached the data extraction stage of the process. A single round of forward snowballing was conducted due to time restrictions. A total of 98 and 655 articles were added to the literature search, from the backward and forward snowballing processes respectively.

For articles which met the inclusion criteria but did not present sufficient data, the corresponding author was contacted with a request for data in an appropriate format for meta-analysis. The total number of articles found in the literature search process was 2545 articles.

Article metadata, including title and abstract, were exported from the results of the literature search for each database (or article in the snowballing process). This data was imported into the Covidence online software environment. Covidence is a tool used to aid systematic reviews by automating much of the data processing and presenting article information in a easily interpreted format. This environment was used for the title and abstract stage of the literature search. Two reviewers conducted this stage in order to address potential bias in the process. For this stage of the review a Cohen's kappa statistic of 0.6 McHugh (2012) and a proportionate agreement of 0.9 were calculated. This figure represents the lower end of "moderate agreement" (McHugh, 2012) and met the requirements of the study protocol. Disagreements on article inclusion between the two reviewers were discussed through notes in the Covidence environment. Satisfactory conclusions were reached for all disagreements.

The full-text review, quality assessment, and data extraction stages were conducted by a single author. The Covidence environment was used to encode articles for metadata, and a spreadsheet was used to extract experimental data. The PRISMA flow diagram for the systematic review process is presented in Fig. 1.

3.3.1. Article quality

A short list of quality criteria were used to assess each included article. The list was developed based on Thomas et al. (2004) and Bowler et al. (2010). The number of quality criteria was necessarily small due to the overlap between the recommendations of the cited sources regarding article quality and the inclusion criteria of the study. Therefore, three quality criteria were developed for this meta-analysis.

- Participant recruitment: Random recruitment - high quality. Self-selection - moderate quality. No discussion - low quality.
- Reported data type: Pre- and post-treatment mean and standard deviation - high quality. Post-treatment mean and standard deviation - moderate quality. Reporting of statistical tests and/or effect sizes - low quality.
- Control of and/or discussion of confounding variables: Inclusion of discussion or controlling for confounding effects - high quality. No discussion - low quality.

Overall, studies were classified as being of high, moderate, or low quality. Low quality studies were excluded from the meta-analysis. However, due to the several inclusion criteria applied before the quality assessment, it was anticipated that low quality studies would not meet the inclusion criteria, and would not be included as part of the literature search.

3.3.2. Heterogeneity

The set of included studies was anticipated to display significant heterogeneity, given the broad nature of particular inclusion criteria. The causes for heterogeneity between reported results include.

- Differing definitions of natural and urban environments
- Several physiological measures of stress
- Varying exposure types, duration, and activities
- Potential population factors
- Missing data or information within articles
- Potential positive publication bias (discussed in Section 4.4.1)

The expected heterogeneity was used to aid in development of the type of extracted metadata, which in turn may be used for subgroup analysis to test the various causes of heterogeneity in the results. Furthermore, the several secondary objectives of this meta-analysis aimed to explore this heterogeneity in the extracted data set.

3.4. Data synthesis

Data processing was undertaken in several discrete steps. The initial data synthesis consisted of analysis of both article metadata and preprocessing of the quantitative results reported in each article. Article metadata included country of study, participant type, mean age, and recruitment method, exposure type (laboratory, immersion, or virtual reality), activity, and duration, use of a stressor, type of natural environment (wild or managed), physiological stress outcome measure and study of confounding variables.

A range of quantitative data types and outcome variables were presented in the studies, with each data type treated separately in order to coherently process the entire data set. A pooled standard deviation was used for between-subjects designs. The method of Lakens (2013) was used for within-subjects design, with an assumption of $r = 0.5$ made according to Fu et al. (2008).

The third step was to pool multiple results from each article into a single representative effect size and variance for each article. Multiple results were reported by the majority of articles due to a wide variety of outcome measures being studied. For example, Li et al. (2011) reported data for the outcome measures of heart rate, heart rate variability, and

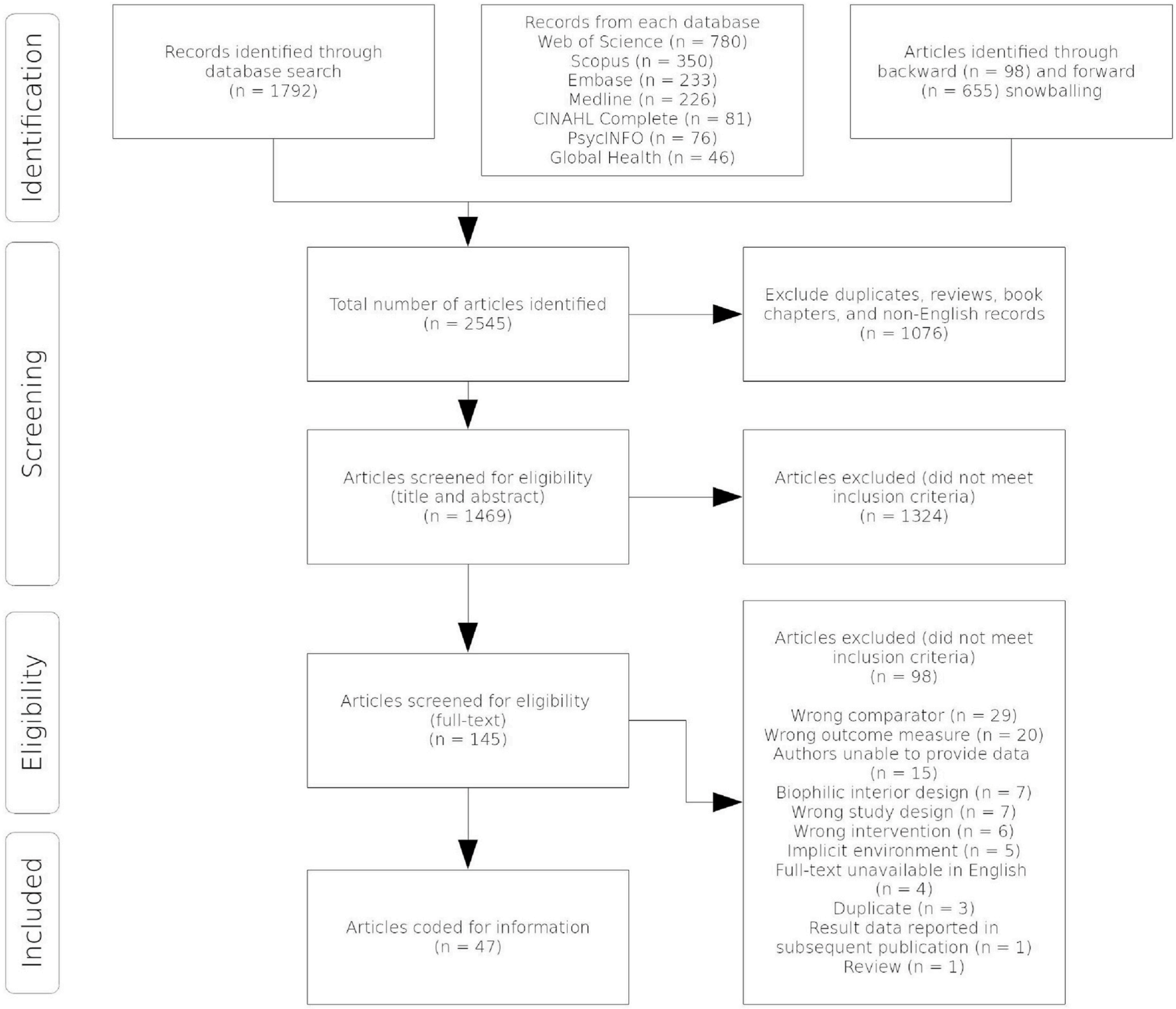

Fig. 1. Flow diagram of the systematic review process.

salivary cortisol. An assumption regarding the correlation coefficient between each outcome measure was required to pool these various outcome measures. As no direct evidence could be found regarding correlation between different measures of stress and sympathetic nervous system activity, a sensitivity test was undertaken. The results of this sensitivity test are reported in Section 4.4.1, with the higher correlation coefficient of $r = 0.75$ between outcome measures selected for the study.

The final step was to conduct the meta analysis, including consideration of publication bias and other sensitivities. The meta-analysis used Cohen's d (Cohen, 1988) as the effect size measure. Standard deviations were calculated by arithmetic average for within-subjects study designs, and pooled standard deviations for between-subjects designs. The variance of the effect size was calculated using the method of Cooper (2010). Two tailed 95% confidence intervals for each effect size were calculated using this variance. The methods and calculator of Lakens (2013) were used to calculate effect sizes for studies that reported a test statistic only (e.g. F-test). A random-effects model (Borenstein, 2009) was used to conduct the meta-analysis. Study results were weighted using the inverse variance method. T^2 was calculated using the method of moments. As discussion in Section 3.3.2, considerable variability across study methods and results was expected. Hence a random-effects model was considered most suitable for this analysis. A discussion of various methods and corrections for potential publication bias is provided in Section 4.4.1.

4. Results

4.1. Article quality

The data set displayed a prevalence of studies with smaller sample sizes, and considerable heterogeneity amongst effect size results. This is best displayed by the funnel plots presented in Section 4.4.1. Whilst the purpose of the present primary meta-analysis is to assist is negating the effect of smaller sample sizes, the effect of small studies on the secondary objectives and subgroup analysis is apparent. This is discussed in Section 4.4.2.

All articles were identified as being of moderate quality. No high quality or low quality articles were included. High quality was not achieved by a number of articles due to self-selection of participants. However, the articles considered to be the highest quality were Geniole et al. (2016); Gidlow, Randall, et al. (2016); Jones et al. (2021); Ojala et al. (2019); Stigsdotter et al. (2017); Lanki et al. (2017); Liu, Wang, Liu, An, et al. (2021). The lowest quality articles were largely driven by the lack of discussion or control of moderating effects, and were identified as Hassan et al. (2018); Tyrväinen et al. (2014); Veitch et al. (2022); Vert et al. (2020). It is recognised that the data set, whilst of acceptable quality relative to the coded indicators of article quality, may present weakness in other areas that are not able to be clearly coded. These factors are discussion throughout this section and summarised in the Limitations section of this article.

4.2. Overall body of literature

A total of 47 articles were included as part of the literature search, published from 2003 onward. The majority of published work was recent, with approximately half of the articles published within the last five years. 25 of the articles originated from Asia, including Japan (15 articles), China (4 articles), South Korea (3 articles), Taiwan (2 articles), and Malaysia (1 article). Europe (16 articles), North America (4 articles), and Australia (1 article) accounted for 21 articles, with a single article of unknown geographic origin. 46 articles originated in the northern hemisphere, with only a single Australian article (Veitch et al., 2022) from the southern hemisphere. Table 2 displays a summary of metadata for the entire data set.

4.3. General description of articles

4.3.1. Reported data and experimental methods

Reported data types and experimental methods varied between articles. Over half (28 articles) reported pre/post data, with 12 articles reporting post data only, and 7 articles reporting a statistical test or effect size. Over three-quarters of articles utilises a within-subjects design, with the remainder being of between-subjects design. Similarly, over three quarters of articles utilised immersion in real environments, with five articles using laboratory simulation, four articles using virtual reality methods, and one article using both laboratory and virtual reality simulation (Park et al., 2020). Participant activity was roughly evenly split between walking (20 articles) and sitting (18 articles), with 8 articles utilising both, and one article studying jogging subjects (Pretty et al., 2005). Classification of environments was conducted according to the description in (Gaekwad et al., 2022), namely “wild” environments, including national parks and state forests, and “human managed”, which

Table 2
Summary of metadata from experimental studies reporting on the relative effect of exposure to natural and urban environments on physiological indicators of stress.

Study	Country	Sample Size	Mean Age	Exp. Type	Env. Type	Activity	Duration
Abdul Aziz et al. (2021)	Malaysia	90	22.9	I	M	W	20 min
Brown et al. (2013)	UK	23	36.9	L	W	S	10 min
Geniole et al. (2016)	Canada	31	24.6	I	M	W	15 min
Gidlow et al. (2016a)	UK	37	40.9	I	M	W	30 min
Grassini et al. (2022)	Finland	24	24.8	L	W	S	12 min
Grazuleviciene et al. (2016)	Lithuania	20	62.3	I	M	W	30 min
Hartig et al. (2003)	United States	112	20.8	I	M	W	50 min
Hassan et al. (2018)	China	60	19.6	I	W	W	15 min
Hedblom et al. (2019)	UK	102	27.0	V	W	S	–
Janeczko et al. (2020)	Poland	40	–	I	M	W	30 min
Jones et al. (2021)	Greece	41	36.6	I	M	W	30 min
Kanelli et al. (2021)	Greece	24	34.9	I	W	W	60 min
Kang et al. (2022)	Japan	9	29.6	I	M	S	10 min
Kobayashi et al. (2019)	Finland	74	Nil	I	–	S	15 min
Kobayashi et al. (2017)	South Korea	348	Nil	I	–	S	15 min
Lanki et al. (2017)	Finland	36	46.0	I	W	B	15 min sit, 30 min walk
Lee et al. (2015)	Japan	12	22.3	I	M	S	15 min
Lee et al. (2011)	Japan	9	21.2	I	W	S	15 min
Lee (2017)	South Korea	18	26.7	L	M	S	18 min
Lee et al. (2009)	Japan	12	21.3	I	W	S	30 min
Li et al. (2011)	Japan	16	57.4	I	M	W	4 h per day
Li et al. (2020)	China	24	56.7	I	M	W	20 min
Liu et al. (2021b)	China	30	23.9	I	W	B	30 min sit, 30 min walk
Navalta et al. (2021)	United States	10	–	I	W	B	30 min sit, 30 min walk
Ojala et al. (2019)	Finland	82	48.3	I	W	B	15 min sit, 30 min walk
Park et al. (2020)	–	32	27.8	L and V	B	S	1 min
Park et al. (2007)	Japan	9	22.8	I	W	B	20 min walk, 20 min sit
Park et al. (2008)	Japan	12	21.3	I	W	S	15 min
Pratiwi et al. (2020)	Japan	12	67.5	I	M	W	11 min–155 min
Pretty et al. (2005)	UK	40	24.6	L	W	O	20 min
Reeves et al. (2019)	UK	34	–	I	M	S	10 min
Shin and Choi (2019))	South Korea	10	60.3	I	M	W	15 min
Song et al. (2019)	Japan	60	21.0	I	M	W	15 min
Song et al. (2013)	Sweden	485	21.8	I	W	S	15 min
Song et al. (2015)	Japan	20	22.3	I	M	W	15 min
Sonntag-Öström et al. (2014)	Japan	20	21	I	M	W	15 min
Stigsdotter et al. (2017)	Sweden	51	41.6	I	W	B	10 min walk, 40 min sit
Tsunetsugu et al. (2013)	Japan	42	21.0	I	W	S	20 min
Tyrväinen et al. (2014)	Finland	77	47.6	I	M	B	15 min sit, 30 min walk
Valtchanov (2010)	United States	47	–	V	W	S	10 min
Veitch et al. (2022)	Australia	20	24.4	I	M	W	30 min
Vert et al. (2020)	Spain	59	29.0	I	M	W	–
Wood et al. (2020)	Japan	12	32.9	L	–	W	30 min
Yamaguchi et al. (2006)	Taiwan	10	23.2	I	W	B	25 min
Yu et al. (2018)	Taiwan	30	–	V	W	S	9 min 30 s
Yu et al. (2020)	Taiwan	34	58.8	V	W	S	10 min
Zeng et al. (2020)	China	30	21.5	I	M	S	15 min

*Note: Dash(–) indicates information not reported. Exp. Type = Exposure Type. For Exposure Type: I = Immersion, L = Laboratory Simulation, V = Virtual Reality. Env. Type = Environment Type. For Environment Type: M = Managed, W = Wild, B = Both. For Activity: W = Walking, S = Sitting, O = Other.

typically covers urban parks. The type of natural environments studied was also roughly evenly split, with 22 articles utilising managed environments and 21 articles utilising wild environments. One article used both types of natural environment (Park et al., 2020), and three articles provided insufficient information to identify the natural environment type (Kobayashi et al., 2017, 2019; Wood et al., 2020). As limited information was provided about the specific environments, the degree of immersion and potential for interference (e.g. traffic noise) was unknown for all studies.

Environment exposure times varied significantly, with a 10–15 min exposure time common (24 articles) and total times ranging from 1 min (Park et al., 2020) to 4 h (Li et al., 2011).

Use of a stressor was rare, given the basis of Stress Recovery Theory as discussed in the Background section of this article. Over 90% of the articles did not use a stressor. Of the five studies that used a stressor, two studies used well-known cognitive tests (Brown et al., 2013; Hartig et al., 2003), one study used minor electrical shocks (Hedblom et al., 2019), one study used an arithmetic test (Valtchanov & Ellard, 2010), and one study used stressful 1-min film clips (Park et al., 2020). In addition, a single study did not use a stressor but did consider a high-stress population (Sonntag-Öström et al., 2014).

4.3.2. Participants

Participant type was reasonably homogeneous throughout the data set. 23 studies sampled from the university student population. Other populations included local professionals and government workers (5 studies). Only 3 studies sampled from the general public (Gidlow, Randall, et al., 2016; Jones et al., 2021; Yu et al., 2018).

Specific samples included 4 studies which considered middle aged and older participants (Li et al., 2020; Pratiwi et al., 2020; Yu et al., 2018; Zeng et al., 2020), 2 studies considering people recovering from coronary disease (Grazuleviciene et al., 2016; Shin & Choi, 2019), and one study which considered patients enrolled at a stress rehabilitation clinic following diagnosis with exhaustion disorder (Stigsdotter et al., 2017). Seven studies did not report on the population from which the sample was drawn.

Likely due to the significant use of university students to draw samples, the median mean participant age across the studies was 26.7. 26 studies tested participants with a mean age under 30 years.

Just under half of the studies did not report on participant recruitment method. Of the 25 studies which did report on recruitment method, use of social media, targeted emails (through university organisations or employment human resources managers), email newsletters, and poster advertisements were the most common methods of recruitment.

The total sample size varied significantly between studies, with the smallest sample size of 9 participants used by Lee et al. (2011) and Kang et al. (2022), and the largest sample size of 485 achieved by Song et al. (2013) through a conglomeration of previous work by the authors. Note that due to participant difficulties and data loss during the studies, the total sample size recruited was often greater than the sample size associated with the reported results for the experimental groups. 32 studies utilised a sample size of less than 50 participants, and 16 studies utilised a sample size of less than 20 participants.

4.3.3. Outcome measures

Studies used several outcome measures related to the physiological effects of stress. These measures were typically related to activation of the parasympathetic and sympathetic branches of the autonomic nervous system, as discussed in Section 1.3. The most frequent outcome measures were heart rate and blood pressure, used by 29 and 26 studies respectively. Systolic, diastolic, and mean values of blood pressure were used. 14 studies measured outcome variables related to heart rate variability (HRV). The most common HRV measure was the high frequency component, followed by the ratio of high frequency to low frequency energy. Three studies measured cerebral blood flow (Kang et al., 2022; Lee, 2017; Park et al., 2007), and a single study measured peripheral oxygen saturation (Zeng et al., 2020).

For salivary and urinary measures, 15 studies measured salivary cortisol. Two studies also measured salivary alpha amylase (Kobayashi et al., 2019; Yu et al., 2018), and one study also measured salivary testosterone (Geniole et al., 2016). A single study utilised urinary measures (Li et al., 2011), namely adrenaline, dopamine, and noradrenaline.

In addition to the more common measures of circulatory function and hormone levels, five studies measured electrodermal activity, and two studies utilised EEG (Hassan et al., 2018; Reeves et al., 2019).

4.4. Data synthesis

4.4.1. Publication bias and sensitivities

Potential sensitivities of the results to various meta-analysis methods and data set properties were studied. These included the correlation between different outcome measures within the same article, publication bias, and meta-analysis methods.

Correlation between outcome measures. The majority of articles reported data from more than one outcome measure. In order to pool these outcome measures into a single value representing the combined results of the article, an assumption on the correlation coefficient between outcome measures was required. A sensitivity test was used to inform the appropriate correlation coefficient to be taken forward in the study. Three correlation coefficients were tested, representing low ($r = 0.25$), moderate ($r = 0.5$), and high ($r = 0.75$) association. A random-effects meta-analysis was conducted on the data set produced by each correlation coefficient. The results of this sensitivity test, displayed in Fig. 2, indicated low sensitivity to the correlation coefficient. A coefficient of $r = 0.75$ was selected as this figure provided the most conservative outcome and, as the various outcome measures were often measuring sympathetic nervous system activity, a moderate to high degree of correlation between measurements was expected.

Publication bias. Both a funnel-plot type method and p-value type method were applied as part of a sensitivity study to detect and correct for publication bias. The results of this sensitivity study are presented in Fig. 3.

The first set of analyses were undertaken on the raw data set. A p-uniform (van Assen et al., 2015) analysis indicated a high effect size. This analysis was conducted using the web application developed by van Aert et al. (2016). The p-uniform test of publication bias did not suggest that publication bias had an effect on the calculated effect size. This result did not necessarily indicate a lack of publication bias in the data set, rather that the effect of publication bias on the calculated effect size was not significant. It is noted that the properties of a data set may result in a negative result for such a test of publication bias when publication bias may indeed have an effect on the calculated combined effect size. A fixed-effect model (Borenstein, 2009) conducted on significant studies only (a secondary result of the p-uniform analysis) indicated a lower but still high effect size. It was understood that a fixed-effect model was not likely to be applicable to the data set, as it was assumed that the population effect size was heterogeneous. However the fixed-effect model result for significant studies only is provided for comparison with the p-uniform method. A random-effects model was finally applied to the data set, resulting in a moderate effect size.

The effect size result for the p-uniform method was larger than both the preferred random-effects model and a comparative fixed-effects model. This was interpreted as the key assumptions of the p-uniform method (fixed population effect, only significant studies included) (van Assen et al., 2015) decreasing the applicability of the method to the raw data set.

In addition to the p-uniform method test of publication bias, the impact of potential publication bias was estimated using two methods based on the concept of the funnel plot (Duval & Tweedie, 2000). A funnel plot (Figs. 4 and 5) was generated as effect size plotted against

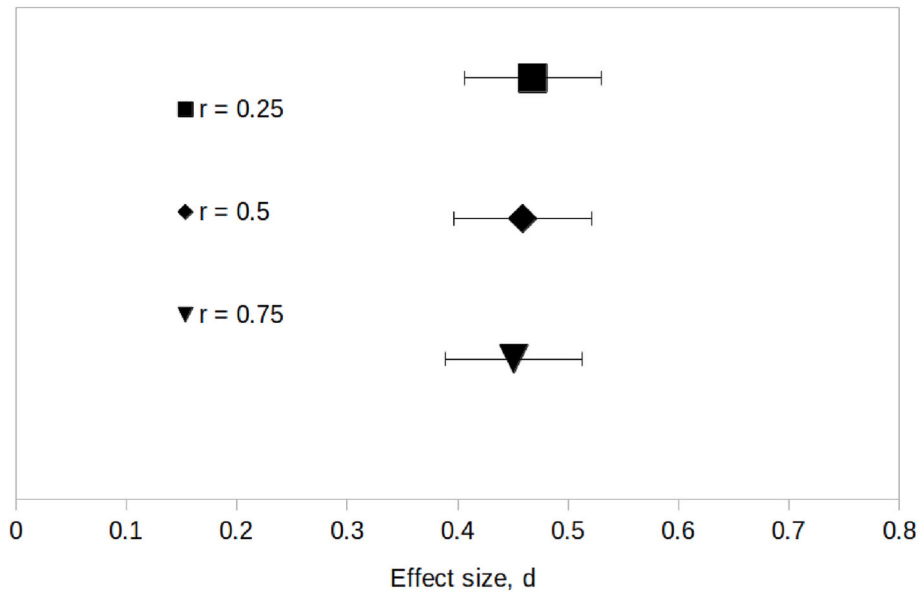

Fig. 2. Effect size results for the correlation coefficient sensitivity test. Error bars represent 95% confidence interval.

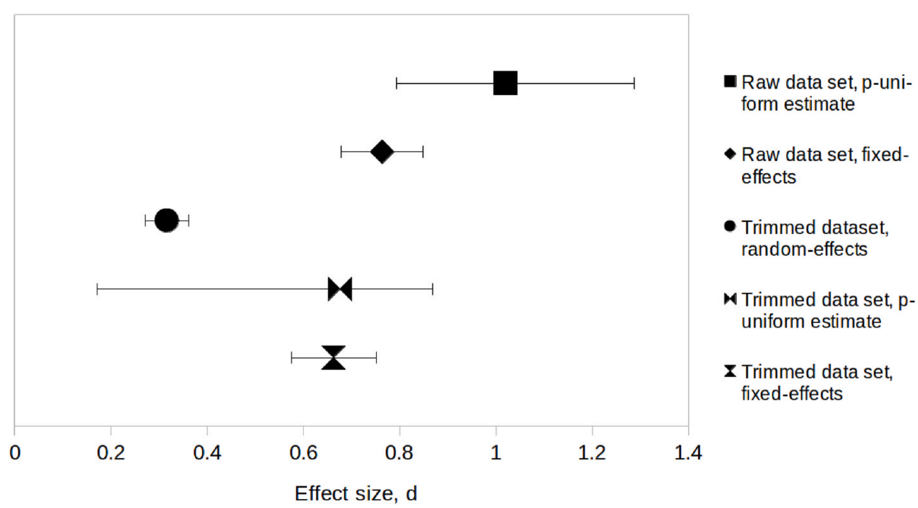

Fig. 3. Effect size results for the publication bias sensitivity test. Error bars represent 95% confidence interval.

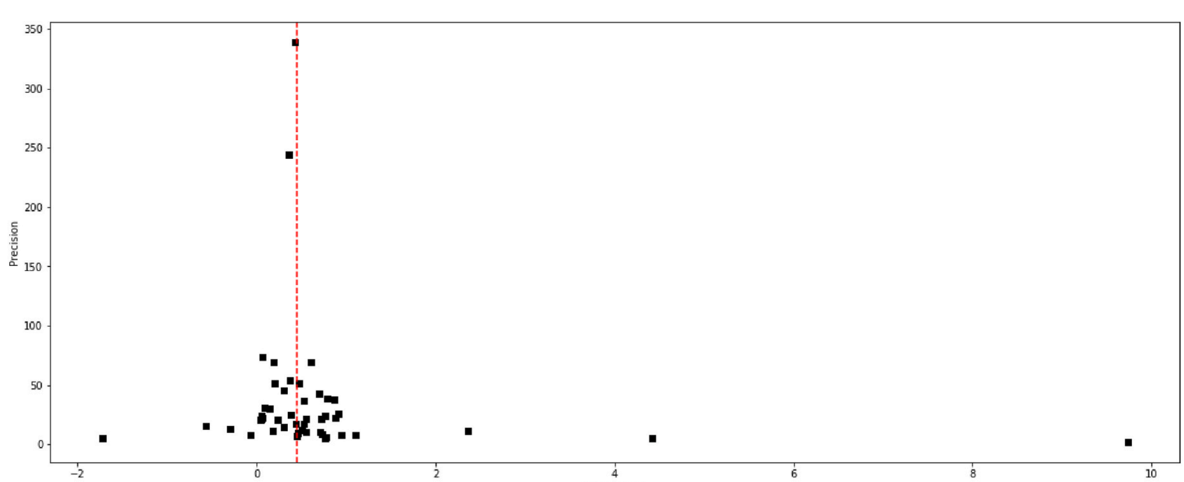

Fig. 4. Funnel plot of entire raw data set.

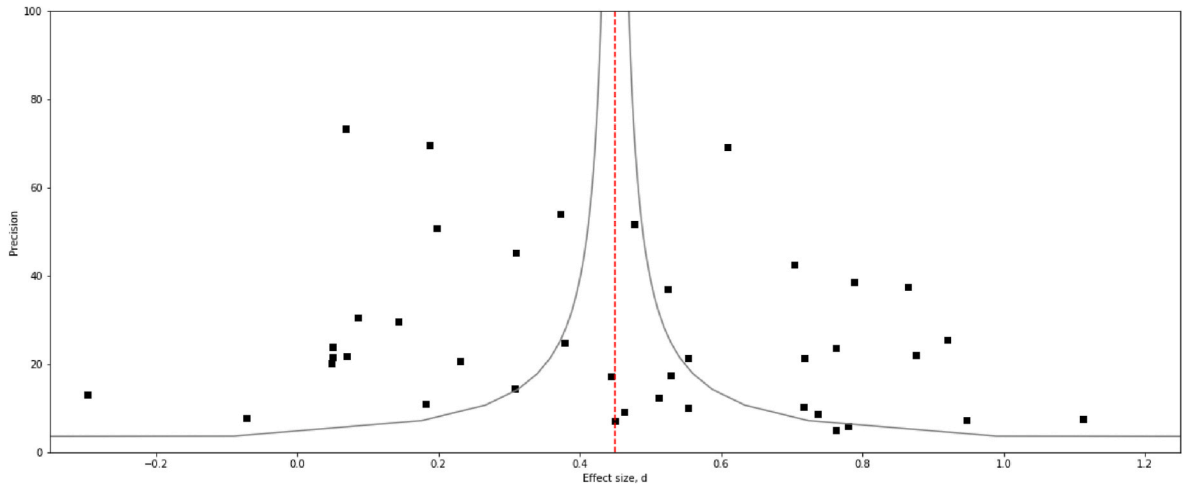

Fig. 5. Detail funnel plot of raw data set. Grey curves represent 95% confidence interval of the effect size.

precision ($1\,/StandardError$) (Egger et al., 1997). The first method used to test asymmetry of funnel plots and therefore publication bias was the regression test of Egger et al. (1997), which provided information on the asymmetry of the funnel plot based on the intercept of a line fitting the data plotted as a weighed effect size against precision. A p-value of less than 0.1 was achieved for the intercept indicating a fail value for Egger's test and funnel plot asymmetry. Secondly, visual inspection of the funnel plot indicated likely asymmetry, with several studies of very large positive effect size potentially influencing the final results.

The limitations of funnel plot based methods in detecting publication bias are recognised. These limitations are often referred to as "small study effects" (Sterne et al., 2000) and are perhaps best summarised in Egger et al. (1997), which indicates that there are many sources of funnel plot asymmetry which are not related to publication bias. However, noting the appearance of the funnel plot, failure of Egger's test, and high effect size estimate of the p-uniform method, a trim-and-fill (Duval & Tweedie, 2000) analysis was undertaken using the linear estimator L_o. A total of 11 studies were trimmed, with a corresponding decrease in effect size result using the random-effects method. Several of the trimmed studies had very high effect sizes, and may have been considered outliers of sorts due to specific experimental methods used in connection with these large effect sizes. These articles are briefly discussed in Section 4.4.3.

A p-uniform analysis and related fixed-effects analysis were then conducted on the trimmed data set only as a sensitivity test. The p-uniform and fixed-effects results were similar, however these results were still significantly higher that the random-effects analysis of the trimmed data set. This result reinforced the interpretation that two key assumptions of the p-uniform analysis, that only significant findings are considered and that the population effect is fixed (van Assen et al., 2015), were the likely causes of the discrepancy between the p-uniform and random-effects analyses. It was also noted that the low bound of the 95% confidence interval of the p-uniform estimate encompassed the random-effects estimate and confidence interval.

Given the results and interpretation of the publication bias sensitivity study, the results of the random-effects meta analysis of the trimmed data set were used as the basis of the results reported herein. This result may be considered conservative as the trim-and-fill method may have been somewhat "aggressive" in removing article data points indicating a larger effect. This was likely due to a mix of small study effects and publication bias being the cause of funnel plot asymmetry. The publication bias study indicates that the true population effect likely ranges between the results of the random-effects analysis to some range upward (i.e. a higher effect).

4.4.2. Results

Effect sizes were calculated for each article using a random-effects method and trimmed data set (refer Section 4.4.1). The variance of the effect size was used to calculate the 95% confidence interval. Results for each article are presented in Figs. 6 and 7. The interpretation of effect size by Cohen (1988) is used herein, namely 0.2 as a small effect, 0.5 as a medium effect, and 0.8 as a large effect. As discussed by Gaekwad et al. (2022), there may be some ambiguity in translating these effects sizes into human well-being.

A small to medium effect was shown regarding the effect of natural environments on decreasing the physiological indicators of stress, as compared to urban environment ($d = 0.32$, $95\%CI = 0.27, 0.36$). This result directly addresses the primary objective of this meta-analysis, and lends credibility to the theoretical foundation discussed in the Background section of this article.

Subgroup analysis was used to address the several secondary objectives of this study. Table 3 presents the results of this analysis. The subgroups were derived from the raw (untrimmed) data set. A random-effect meta analysis was conducted on each subgroup. Q-tests (Borenstein, 2009) were conducted to test for potential differences between subgroups when more than two subgroups were present. A z-test was used when two subgroups were present. The Q-test and z-test are analogous to ANOVA and t-tests respectively between group sums rather than primary data Borenstein (2009). Where Q-tests indicated a significant difference between subgroup effect sizes, a set of paired z-tests was used to identify specific differences amongst subgroups.

Exposure to environment. The secondary objective addressing the type of exposure to the environments (immersion, laboratory simulation, or virtual reality) was addressed through subgroup analysis (refer Fig. 8). Immersion in the environment resulted in a medium effect ($d = 0.48$, $95\%CI = 0.42, 0.55$), laboratory simulation displayed a medium effect ($d = 0.55$, $95\%CI = 0.16, 0.94$), and virtual reality exposure displayed a small effect ($d = 0.27$, $95\%CI = 0.15, 0.40$). Total sample sizes were small for both the laboratory and virtual reality subgroups, with 149 and 245 participants respectively. The laboratory subgroup results in particular displayed a high degree of uncertainty. Furthermore, one of the articles in the laboratory subgroup (Lee, 2017), reported very high effect sizes of over 10 times the typical effect size for the subgroup. This study used a unique outcome measures of cerebral blood flow. The validity and potential confounding effects of this article and its impact on this result are discussed in Section 4.4.3.

The Q-test of the three exposure subgroups indicated a significant difference ($Q = 11.22$, $df = 2$, $p = 0.004$). However a set of paired z-tests were conducted on the subgroups with no indication of significant difference between subgroups ($p = 0.13$ comparing immersion and virtual

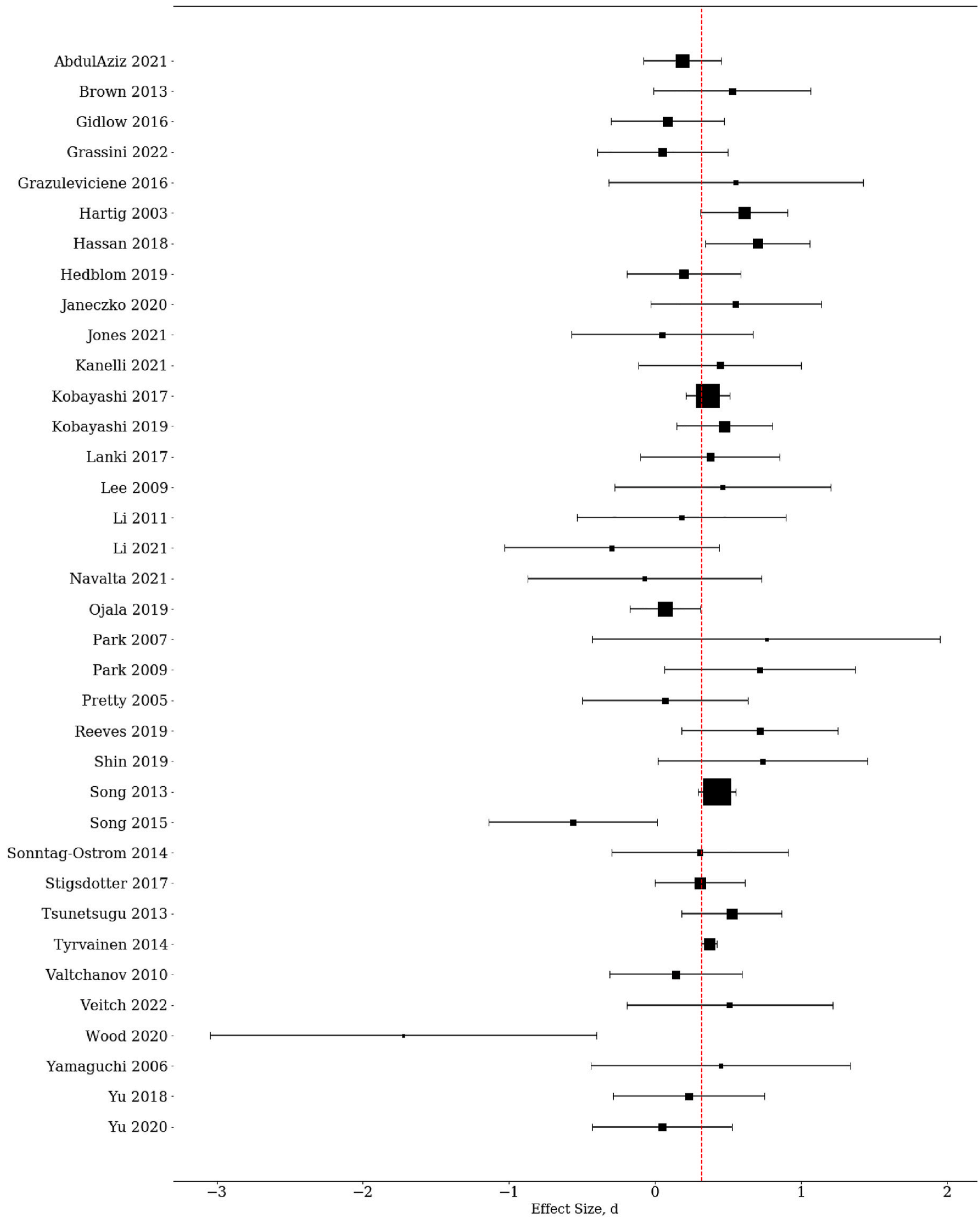

Fig. 6. Forest plot of effect size results. Effect size, d, on x-axis. Error bars represent 95% confidence interval. Weighted average effect size plotted as dashed red line. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

reality). Inspection of the means and confidence intervals may indicate that immersion in natural environments is more effective than virtual reality in reducing stress. However more data regarding the effectiveness of virtual reality exposure are required. Implications of the laboratory exposure results are unclear due to the high degree of uncertainty.

Participant health conditions. The secondary objective related to participants with health conditions was also achieved through subgroup analysis. However, only 3 studies with a total sample size of 81 participants were included as part of the health condition subgroup (Grazuleviciene et al., 2016; Shin & Choi, 2019; Stigsdotter et al., 2017). The uncertainty associated with this subgroup analysis was therefore high. A medium effect was achieved (d = 0.39, 95%CI = 0.29, 0.53), compared to a medium effect demonstrated by the subgroups defined by participants not having health conditions (d = 0.45, 95%CI = 0.39, 0.52). A z-test indicated no significant difference between the subgroups (p = 0.7). Further information on studies including health status as a confounding variables is provided in Section 5.1.3.

Experimental method. Two variables within experimental methods

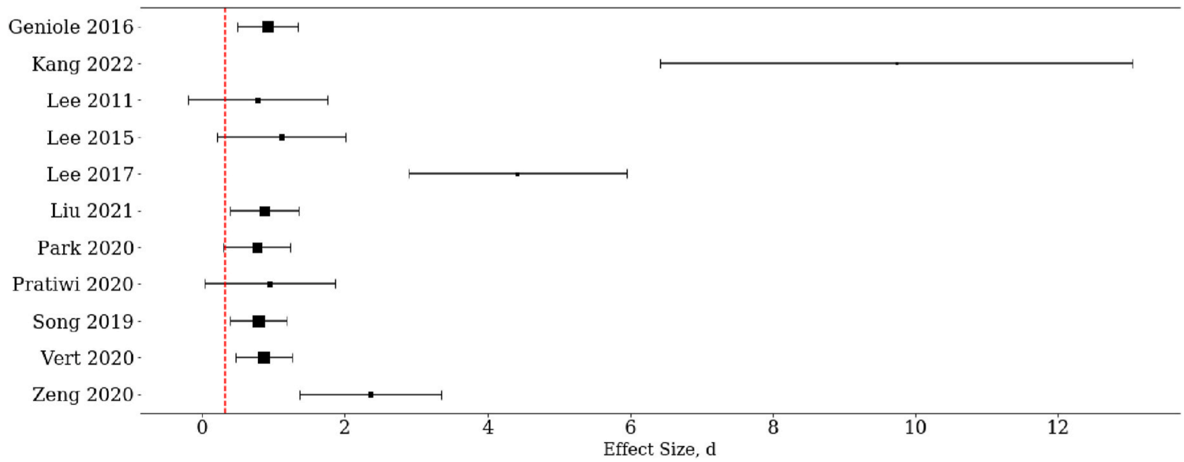

Fig. 7. Forest plot of effect size results for the 11 studies trimmed for correction of potential publication bias. Effect size, d, on x-axis. Error bars represent 95% confidence interval. Weighted average effect size plotted as dashed red line. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3
Summary of random-effects meta-analysis results for subgroups.

Data subset	No. of Articles	n	Effect size, d	95%CI
Raw data set	47	2430	0.45	0.39, 0.51
Trimmed data set	36	2128	0.32	0.27, 0.36
HR	19	968	0.42	0.32, 0.52
HRV	14	435	0.62	0.43, 0.81
BP	24	921	0.39	0.3, 0.49
EDA	4	207	0.19	0.08, 0.3
Salivary cortisol	15	738	0.52	0.38, 0.67
Salivary alpha-amylase	2	40	0.29	0.06, 0.51
Immersion	37	2068	0.48	0.42, 0.55
Laboratory simulation	6	149	0.55	0.16, 0.94
Virtual reality	5	245	0.27	0.15, 0.4
Health conditions	3	81	0.39	0.26, 0.53
Nil health condition	44	2349	0.45	0.39, 0.52
Stressor	6	367	0.42	0.32, 0.52
Nil stressor	41	2063	0.46	0.39, 0.53

(outcome variable and use of a stressor) were tested. A medium effect was demonstrated by studies measuring heart rate ($d = 0.42$, 95%CI = 0.32, 0.52), heart rate variability ($d = 0.62$, 95%CI = 0.43, 0.81), and salivary cortisol ($d = 0.52$, 95%CI = 0.38, 0.67). In comparison, blood pressure demonstrated a low to moderate effect ($d = 0.39$, 95%CI = 0.30, 0.49), and electrodermal activity demonstrated a low to negligible effect ($d = 0.19$, 95%CI = 0.08, 0.30). Refer Fig. 9. A Q-test indicated a significant difference between the subgroups ($Q = 14.4$, $df = 5$, p = 0.01). A set of paired z-tests indicated a single significant difference (p = 0.048) comparing HRV and EDA. It is recognised that comparative significance testing of different outcome measures is of limited practical use.

This result indicates that particular outcome variables are not significantly more effective than other variables in demonstrating the physiological stress response to natural environments, as compared to urban environments. However the small sample size of the EDA and salivary alpha-amylase subgroups ($n = 207$ and $n = 40$ respectively) warrants further investigation into these outcome variables and may call the significance of the comparative HRV and EDA result into question.

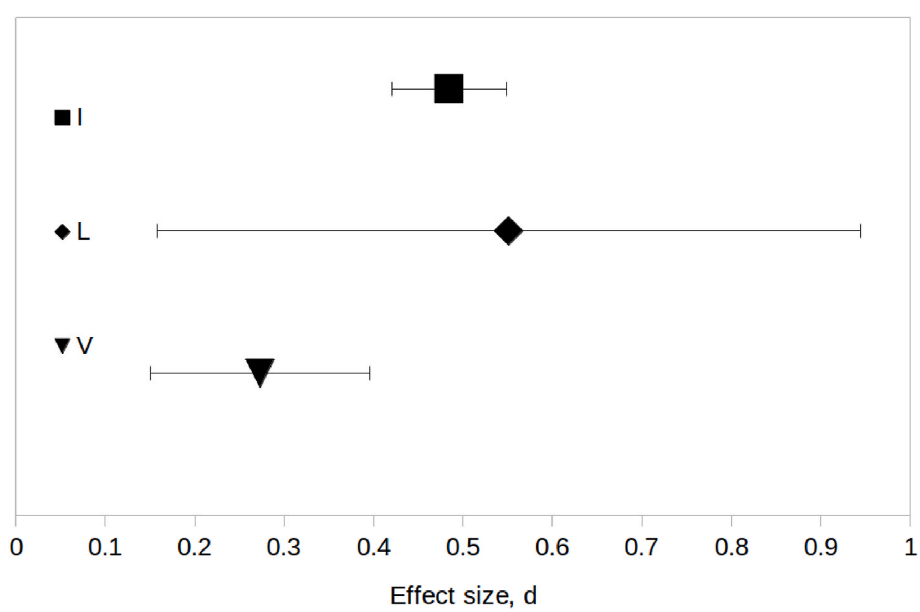

Fig. 8. Effect size results for the subgroup analysis of exposure type. Error bars represent 95% confidence interval. I = Immersion, L = Laboratory Simulation, V = Virtual Reality.

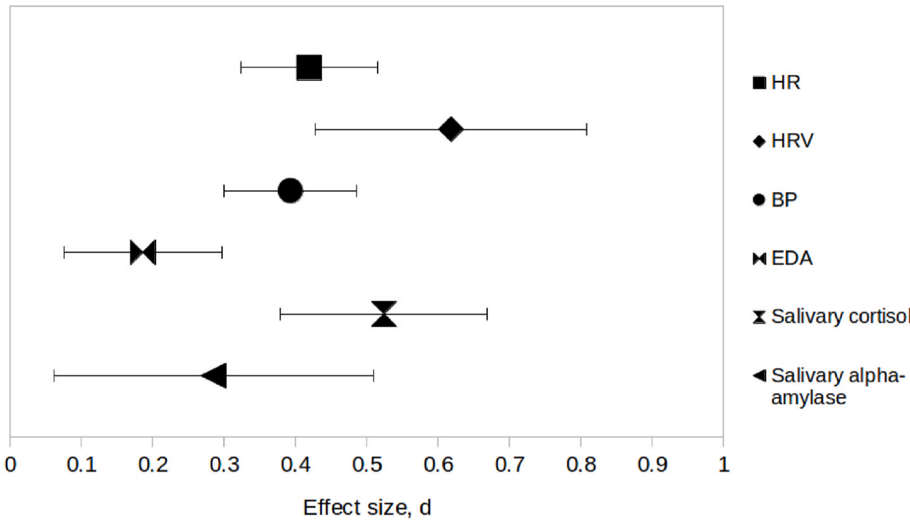

Fig. 9. Effect size results for the subgroup analysis of outcome measure. Error bars represent 95% confidence interval.

A subgroup of six studies were identified as using a stressor in their experimental procedure. Stigsdotter et al. (2017) was included in this subgroup as, although no stressor was used, the study considered participants who attended a stress rehabilitation clinic and were diagnosed with exhaustion disorder. This subgroup demonstrated a moderate effect ($d = 0.42$, 95%$CI = 0.32, 0.52$). The subgroup for studies which omitted a stressor as part of their experimental procedure also demonstrated a moderate effect ($d = 0.46$, 95%$CI = 0.39, 0.53$). A z-test indicated no significant difference between these subgroups ($p = 0.7$). This may indicate that use of a stressor is not required to demonstrate the benefits of exposure to natural environments. The implications of this result for Stress Recovery Theory are discussed in the next section.

4.4.3. *Confounding effects and data interpretation*

Further to the discussion of article and data set quality, the results were further reviewed to highlight potential confounding effects or unusual data points.

The articles Kang et al. (2022) and Lee (2017) warranted further investigation due to their high effect sizes in conjunction with sharing the same research team and unique outcome variable (cortical blood flow). Inclusion criteria and quality checking allowed these articles to remain included within the raw data set, however both articles were omitted from the trimmed data set, due to their high positive effect size results. Although there is no valid reason to exclude these papers within the methodology of the present study, their potential confounding effect is noted and implications on the subgroup analysis must be considered.

The various subgroup analyses may also have been influenced by confounding effects. Several subgroups not only contain few studies, but also feature a low total sample size. For example, the EDA subgroup for study of different outcome measures contains four studies and a total sample size of 207 participants. The smaller number of studies may result in the dominance of a particular study, or style of study (e.g. methodological approach).

These results could imply that a particular subgroup is not a reasonable “average” of studies available, and may render difficulty in drawing clear conclusions from such a subgroup. Furthermore, the small total sample size results in increased uncertainty of results for many subgroups.

5. Discussion

5.1. *Findings*

5.1.1. *Effect of environment*

The meta-analysis identified a small to medium effect of natural environment exposure in reducing physiological stress, in comparison to urban environments. This outcome directly addresses the primary research question. With regards to the supporting theoretical body discussed in the background section of this article, the general premise of Stress Recovery Theory is supported. The Biophilia Hypothesis is also supported, however as biophilia is largely posited as an emotional connection to nature (as discussed in Background), evidence regarding physiological stress reduction may not be as strong in support.

5.1.2. *Effect of exposure type*

The results indicate that laboratory exposure may have a comparable effect to immersive exposure. However, as discussed in Section 4.4.3, two key articles forming part of the laboratory subgroup likely introduce strong confounding effects. Furthermore, the outcome regarding the effects of laboratory exposure on physiological stress may be due to the small number of articles and small total sample size.

Similarly, the virtual reality cohort is small, with 4 articles and 250 participants included. In general, there is less heterogeneity in the virtual reality subgroup as compared to the laboratory simulation subgroup. Effect sizes of individual studies are low, with the lower estimate of the 95% confidence interval often negative. The exception to this general description is Park et al. (2020), which reported a large effect for heart rate variability ($d = 1.5$, 95%$CI = 1.4, 1.7$), and high confidence (but low effect sizes) for measures of heart rate and electrodermal activity.

In terms of the secondary objectives related to exposure type, it is unclear but likely that immersion is more effective than simulation of environments in reducing stress.

5.1.3. *Effects on people with existing health conditions*

No significant difference was indicated between participants with health conditions and participants who did not report existing health conditions. The health conditions subgroup consisted of 3 articles with a total of 202 participants. There are likely to be confounding effects present in this small subgroup, as the small number of articles is unlikely to represent a fair average across the subgroup.

In order to further address this uncertainty, articles which discussed health status as a confounding effect were reviewed. Two articles were identified. Jones et al. (2021) used the health survey of Ware et al. (1996) as part of baseline profiling of participant physical and mental health. No confounding effect of health status was found. Reeves et al. (2019) used the Holmes and Rahe Stress Inventory (Holmes & Rahe, 1967) as part of baseline profiling of participants into a high stress group and a low stress group. The results indicated that environment had a significant effect on heart rate for high stress individuals only. However, no effect of environment on either group was observed for heart rate variability, electrodermal activity, or EEG. Hence, the further review of articles did not reduce the uncertainty regarding the effects of natural environments on people with health conditions, and no clear response to the secondary objective was obtained.

5.1.4. Experimental methods

The implications of the results for the secondary objective regarding specific experimental methods are mixed. Use of a stressor as part of the experimental method and use of specific outcome variables are discussed.

A key aspect of Stress Recovery Theory is that the greatest benefit of exposure to the natural environment on stress occurs when humans are already stressed. That is, nature helps return humans to a less stressed state, faster than without exposure to nature. Noting this, there is a conspicuous lack of studies on stressed participants or that use a stressor as part of their experimental method. The results of the meta-analysis indicated no significant difference in the effect between studies that used a stressor and studies that did not use a stressor in the experimental methodology. This result indicates that the stress state of participants prior to exposure to nature is not relevant to the effect of nature on human stress. This outcome directly contradicts one of the key components of Stress Recovery Theory. It is noted that the stressor subgroup consisted of 6 articles and a total of 367 participants. There is a degree of heterogeneity within this subgroup, with effect size estimates ranging from $d = 0.19$ to $d = 1.5$. Further work on the effects of natural environments on participants at varying levels of stress is required.

Considerable heterogeneity amongst outcome variables was observed, however no significant difference was identified. Heart rate, heart rate variability, and salivary cortisol are recommended measures of physiological stress for further work in the area. Blood pressure, a common measure (26 out of 47 articles) was shown to have a lower sensitivity. In general, blood pressure appears to be a common measure in the literature, with 10 of 36 articles identified by Corazon et al. (2019) and 22 of 43 articles identified by Kondo et al. (2018) using blood pressure as a measure. The results of this meta-analysis conflict with the conclusions of Kondo et al. (2018), which indicated both heart rate and blood pressure as sensitive measures and heart rate variability as an insensitive measure. The EDA subgroup may once again be affected by confounding variables, as only 4 articles with a total sample size of 207 participants were included in the subgroup.

5.2. Limitations

A significant body of research was identified through the literature search, lending credibility to the results presented herein. Article and data reporting quality was generally transparent and of sufficient quality to facilitate iterative research. The present study was conducted with the view of reducing uncertainty in the field, however several latent limitations in method and data set are present. These limitations increase the uncertainty associated with some of the conclusions of this study. Uncertainty was discussed in the body of this article where appropriate, and is summarised in this section.

Methodological limitations were associated with the challenge in detecting and accounting for publication bias in the data set. A sensitivity test approach was used to provide transparency and conservatism, however the overall impact of publication bias on the data set remained somewhat unclear. In addition, parts of the utilised search methodology are also limitations of this study. The search keywords used terms associated with stress, rather than terms associated with the specific outcome variables. This was due to the physiological indicators being informed by the included articles. No specific search for grey literature was conducted due to resource limitations. Inclusion of more grey literature in the data set would have aided in reducing the uncertainty associated with publication bias. It was also not possible to retrieve data for 15 articles from authors who did not present appropriate data in their articles.

There are several key limitations to the data set obtained. Significant heterogeneity was observed, likely caused by "small study effects" as previously discussed. The various subgroup analyses may have been influenced by confounding effects due to small numbers of articles and small total sample sizes for a number of subgroups. This may have resulted in some subgroups not representing a fair "average", but being affected by confounding variables. A number of smaller studies demonstrated very high effect sizes, increasing the uncertainty in the subgroups that these studies belonged to. It is noted that these high effect sizes were trimmed from the raw data set when accounting for publication bias, hence they do not influence the primary meta-analysis.

Regarding the methodology of included studies, more information on the specific properties of the test environments would facilitate more granular study into the effects of varying types of natural and built environments, as highlighted by Gaekwad et al. (2022). Finally, the prevalence of participant self-selection may result in a significant level of bias to the results. This limitation is also noted in previous work by Yao et al. (2021) and Corazon et al. (2019). It is recommended that future studies recruit participants using random methods and from a wider pool to reduce the possibility of selection bias.

6. Recommendations for future research

There are several recommendations for future research synthesised from the results, largely related to shortcomings in the included data set. Arguably the most significant work would be to test the effects of use of a stressor. This would serve to further the concepts present in Stress Recovery Theory. Considering populations with health conditions, especially stress-related health conditions, would also serve to further current theoretical concepts.

In terms of experimental design, larger, randomly recruited samples will serve to increase confidence and study quality. Studies which directly compare the effects of laboratory or virtual reality against immersion in environments would also be welcome, as non-immersive exposures may enable larger sample sizes to be included with limited resources. Supplementary information on the type of natural and urban environments would be welcome to enable further classification of environmental exposure.

Further meta-analyses of the topic are recommended to focus on key subsets of the available data set, where small study effects and resultant heterogeneity may have less of an impact. This may include particular exposure types or environments.

7. Conclusion

Through isolating and consolidating the physiological impacts of exposure to nature, this work has broadly supported the current relevant theoretical landscape whilst querying aspects of theoretical content and providing direction for future work. The data set was found to feature significant heterogeneity and small sample sizes, which presented challenges to the certainty to the analysis.

A small to medium effect of natural environments in reducing physiological stress, in comparison to urban environments, was determined. This outcome achieves the primary objective of this work, and broadly supports Stress Recovery Theory and the Biophilia Hypothesis. However, there was a lack of clarity regarding the secondary objectives which limits total support of Stress Recovery Theory. Namely, use of a stressor as part of the experimental method was not found to have a larger effect in comparison to experimental methods which did not use a stressor. However, the subgroup size for articles which used stressors as part of their methodology was small. Similarly, a small subgroup of participants with health conditions was also assessed, with uncertain results as to the effect of health state on the ability of natural environments to reduce stress. In general, the results of these two secondary objectives seem to indicate that the same benefit of nature is achieved regardless of the stress or health state that the participant is in.

The meta-analysis indicated no significant difference between exposure types. Interpretation of the data set may indicate that immersion is the most effective, and virtual reality the least effective. Laboratory simulation may be comparable to or less than immersion in the environment. The overall validity of this outcome is uncertain due to the aforementioned potential confounding effects.

Subgroup analysis of various outcome measures indicated no significant difference between outcome measures.

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Declarations of competing interest

The authors declare no competing interests.

Author contributions

Conceptualisation: JSG; Methodology: JSG; Software: JSG; Investigation: JSG, ASM; Formal analysis: JSG; Visualisation: JSG; Supervision: PBR; Writing - Original Draft: JSG; Writing - Review & Editing: JSG, PBR, ASM.

Data availability

The article data set generated by this study can be found in an Open Science Framework data repository (https://osf.io/tnhfp).

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The authors would like to acknowledge and pay our respects to the Traditional Owners of the lands and waters that we live and work on across Australia and pay our respect to Elders past and present. We recognise that Aboriginal and Torres Strait Islander peoples have made and will continue to make extraordinary contributions to all aspects of Australian life including culture, economy, and science.

Appendix A. Database search strings

Scopus

TITLE-ABS-KEY (”natural environment*”) OR TITLE-ABS-KEY (”connect* to natur*”) OR TITLE-ABS-KEY (”connect* with natur*”) OR TITLE-ABS-KEY (biophil*) AND TITLE-ABS-KEY (effect*) OR TITLE-ABS-KEY (impact*) OR TITLE-ABS-KEY (benefit*) OR TITLE-ABS-KEY (measure*) OR TITLE-ABS-KEY (outcome*) OR TITLE-ABS-KEY (influenc*) AND TITLE-ABS-KEY (stres*) OR TITLE-ABS-KEY (distress*) OR TITLE-ABS-KEY (arous*) AND TITLE-ABS-KEY (occupant) OR TITLE-ABS-KEY (participant*) OR TITLE-ABS-KEY (subject) OR TITLE-ABS-KEY (subjects)

Web of Science (Core Collection)

ALL=((”natural environment*” OR ”connect* to natur*” OR ”connect* with natur*” OR biophil*) AND (effect* OR impact* OR benefit* OR measure* OR outcome* OR influenc*) AND (stres* OR distress* OR arous*) AND (occupant OR participant* OR subject OR subjects))

Web of Science (Medline)

TS=((”natural environment*” OR ”connect* to natur*” OR ”connect* with natur*” OR biophil*) AND (effect* OR impact* OR benefit* OR measure* OR outcome* OR influenc*) AND (stres* OR distress* OR arous*) AND (occupant OR participant* OR subject OR subjects))

EBSCO (PsychINFO, Global Health, CINAHL Complete)

(”natural environment*” OR ”connect* to natur*” OR ”connect* with natur*” OR biophil*) AND (”effect*” OR ”impact*” OR ”benefit*” OR ”measure* OR ”outcome* OR ”influenc*”) AND (”stres*”) OR (”distress*”) OR (”arous*”) AND (”occupant” OR ”participant*” OR ”subject” OR ”subjects”)

Embase

(”natural environment*” OR ”connect* to natur*” OR ”connect* with natur*” OR biophil*) AND (effect* OR impact* OR benefit* OR measure* OR outcome* OR influenc*) AND (stres* OR distress* OR arous*) AND (occupant OR participant* OR subject OR subjects)

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