Title

The psychophysiological reactivity to beaches vs. to green and urban environments: insights from a virtual reality experiment

Authors

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1 Introduction

Coastal destinations are popular resources for recreation and health (Gammon & Jarratt, 2019). More than 47% of the total recreational overnight stays in the European Union are spent in coastal municipalities (2012-2022; Eurostat, 2022),[1] and stress-relief is one of the main experiences that people report when visiting the coast (Ashbullby et al., 2013; Bell et al., 2015). It is reasonable to assume that internal physiological mechanisms are causing these perceived benefits. However, to strengthen the evidence of these effects, it is vitally important to acquire more knowledge of the physiological mechanisms (Frumkin et al., 2017; H2020 SOPHIE Consortium, 2020).

The physiology of stress is regulated by the central nervous system, which perceives the environment as calming or arousing based on the information that it receives from the different sensory organs (Cardinali, 2018; Godoy et al., 2018). Depending on the perceived context, the central nervous system increases or decreases the level of arousal by up- or downregulating pathways of the somatic nervous system and the sympathetic and parasympathetic branches of the autonomic nervous system (Chrousos, 2009; Godoy et al., 2018). The arousal may have a valence that is negative (e.g., during stress) or positive (e.g., during excitement). The pathways that have proven to be highly sensitive to changes in arousal and that can be relatively easily measured by non-invasive procedures include those that regulate the heart rate, heart rate variability, sweat production, blood pressure, breathing rate, and muscle tone, among others (Berto, 2014; Corazon et al., 2019; Haluza et al., 2014; Jo et al., 2019; Shuda et al., 2020). Importantly, measuring multiple of these endpoints simultaneously can provide complementary insights about the underlying functional regulatory mechanisms in response to the environment (Cacioppo et al., 2007; Ulrich et al., 1991).

Beaches are among the most effective coastal environments for reducing stress and improving mood (Ashbullby et al., 2013; Bell et al., 2015; Hipp & Ogunseitan, 2011; Hooyberg et al., 2022; Peng et al., 2016b, 2016a; Severin et al., 2022; White et al., 2010; Wyles et al., 2016), but only four studies have investigated how beaches influence the physiology of stress (Anderson et al., 2017; Triguero-Mas et al., 2017; Vert et al., 2020; White et al., 2015). Furthermore, the participants in three of these four studies were physically active (e.g., roaming free; Triguero-Mas et al., 2017; Vert et al., 2020; White et al., 2015), while physical activity may activate the same physiological pathways as those involved in the stress-response (Dahn & And, 2005; Katayama & Saito, 2019; Miyamoto et al., 2022; Triguero-Mas et al., 2017). Virtual reality provides a valid alternative for environmental exposure in the lab in an almost equally immersive way, and this while the participant can remain stationary (Annerstedt et al., 2013; Browning et al., 2021; Browning, Mimnaugh, et al., 2020; Browning, Shipley, et al., 2020; Gao et al., 2019; Litleskare et al., 2020; Tanja-Dijkstra et al., 2018; White et al., 2018; Yeo et al., 2020). Three of the four studies that tested the physiological responses to beaches also tested the responses to green environments, but none of these studies seem to have assessed analytically whether the effects of the beaches differed from those of the green environments (Anderson et al., 2017; Triguero-Mas et al., 2017; White et al., 2015). Additionally, only cardiovascular and electrodermal physiological responses have been measured (Anderson et al., 2017; Triguero-Mas et al., 2017; Vert et al., 2020; White et al., 2015), and knowledge of muscular and respiratory responses would provide more comprehensive insights (Cacioppo et al., 2007). On top of these issues, the law of initial values states that the magnitude of any physiological response depends on the pre-stimulus level of that parameter (Block & Bridger, 1962; Wilder, 1958). This emphasizes the importance of carefully considering each participant's initial level of stress when measuring the physiological pathways of stress. Altogether, no study has yet compared how the beach impacts cardiovascular, respiratory, and muscular pathways differently than outdoor urban and green

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[1] Municipalities that border the sea or have half of their territory within 10 kilometers of the sea.

environments, while excluding physical activity from the exposure and considering that the effect sizes depend on the initial levels of stress of the participants.

The current study aimed to investigate how diverse physiological parameters of stress respond differently to beaches, green, and outdoor urban environments for people with different and naturally varying levels of initial stress. The physiological parameters of interest were chosen to be indicative of diverse autonomic and somatic innervations and included the heart rate, high-frequency heart rate variability (HF-HRV), skin conductance responses (SCR), mean arterial pressure (MAP), breathing rate, and upper trapezius muscle tone. Since physiological parameters display solely arousal and not valence, also self-reported parameters of the positivity and negativity of the situation were measured: i.e., positive and negative mood, perceived stress, and the perceived quality of the environment for stress-recovery. To assess the effects of the initial level of stress, the stress level of the past week was included as an essential moderating factor in the analyses.

We hypothesized that the virtual exposure to the beach would result in a lower physiological arousal and improved self-reported parameters compared to the urban and green environments. Any change from pre- to post-stimulus would be prone to floor and ceiling effects depending on the stress level in the past week.

2 Materials and methods

2.1 Study design and protocol

This study adopted a randomized cross-over design with two periods (VR1 and VR2), three treatments (beach, green, or urban exposure), and four randomized sequences (beach-green, beach-urban, green-beach, and urban-beach; Figure 1). The procedure consisted of a habituation period, the two exposures with two rest periods before each exposure for physiological baseline measurements, and measurement periods before (T0), in-between (T1), and after (T2) each exposure to measure the self-reported parameters (Figure 1). To minimize possible carryover effects between the two periods, T1 also served as a washout period.

Changes in the physiological parameters of stress were measured continuously throughout the experiment via the electrocardiogram (for heart rate and HF-HRV), skin conductance (for SCR), pulse plethysmography (for MAP), respiration signal (for breathing rate), and electromyogram (for upper trapezius muscle tone). Calculations on these signals were done for two 2-minute sections in the 5-minute baseline and eight 2-minute sections during the 16-minute exposures (Figure 1). These sections and their duration were chosen based on standard guidelines for measuring psychophysiological parameters and to be able to detect both slow and rapid changes during the baselines and exposures (Benedek & Kaernbach, 2010; Berntson et al., 1997; Laborde et al., 2017; Malik et al., 1996).

The self-reported positive and negative mood and perceived stress were measured via questionnaires at T0, T1, and T2 to compare the changes from pre-exposure to post-exposure (Figure 1). For these parameters, T1 served as both a post-measurement for the first exposure and a pre-measurement for the second exposure. The perceived quality of the environment for relaxation was assessed via a questionnaire at T1 and T2 about the preceding exposures (Figure 1).

A week before the experiment, an online questionnaire assessed the participants’ demographics, previous environmental exposures, state mental health, and personality. To be noted is that the experiment included additional continuous physiological measurements and cognitive assessments at the ends of T0, T1, and T2. The authors consider that these alterations could not have had an impact on the results. The study was conducted by The Code of Ethics of the World Medical Association for experiments involving humans (the Declaration of Helsinki) and was approved by Ghent University’s Medical Ethical Committee. The experiment took place on workdays starting at 9 a.m., 12 p.m., or 3 p.m. between July 7th and September 24th, 2021, at the Flanders Marine Institute in Ostend or at the Ghent University Hospital in Ghent.

Please display Figure 1 in color online and in color in print. Please print this figure fitting 2 columns.

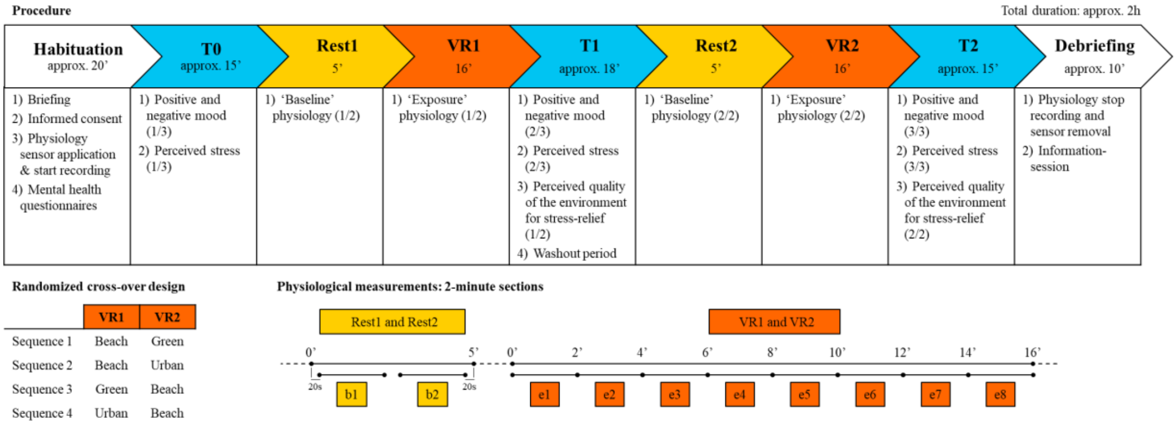

Figure 1: The procedure of the virtual reality (VR) experiment, the sequences of the randomized cross-over design, and the two-minute sections on which the analysis of the physiological measurements were based. The enumerations of the actions listed beneath the steps in the procedure reflect the actual order of these actions. T1 served as washout period to minimize possible carry-over effects between the first (VR1) and second (VR2) VR exposure.

2.2 Participants and recruitment

The virtual reality experiment was carried out on 164 healthy adults (18-65 years old, 68% female,

		N per level or M	
Parameter	**Levels or [Range]^a**	**Beach = Total N = 164**	**Green N = 55**
Design			
Period	First VR, Second VR	81, 83	28, 27
Experiment location	Ghent, Ostend	128, 36	45, 10
Sampling rate	512 Hz, 256 Hz	123, 41	43, 12
Demographics			
Age	[18-65]	34.93 (13.23)	35.62 (13.94
Sex	Male, Female	53, 111	17, 38
SES	The same as my peers, Much better than my peers, Better than my peers, Worse than my peers, Much worse than my peers	96, 11, 42, 14, 1	29, 4, 15, 7,
Smoking status	Non-smoker, Former smoker, Smoker	137, 14, 13	44, 7, 4
BMI	[0-∞]	24.23 (4.12)	23.58 (3.36)
Civil status	Single, In a relationship, Living together, Married, Widow, Divorced	52, 43, 27, 37, 2, 3	19, 12, 10, 1
Occupation	Student, Working, None	46, 113, 5	17, 37, 1
Net household income	<€1000/month, €1001-2000/month, €2001-3000/month, €3001-4000/month, €4001-5000/month, €5001-6000/month, >€6000/month	4, 26, 35, 29, 32, 20, 18	3, 7, 10, 13,
Physical activity level (IPAQ)	[0-∞]	2428.01 (3239.22)	2455.1 (251
Residential blue exposure	Every day, A lot, Moderately, Seldom, Never	12, 20, 27, 58, 8	4, 6, 10, 20,
Residential green exposure	Every day, A lot, Moderately, Seldom, Never	46, 59, 43, 16, 3	14, 24, 13, 6

Residential coastal proximity	0-5km, >5-20km, >20-50km, >50-100km, >100km	14, 8, 64, 64, 14	4, 2, 21, 24,
DASS			
Depression	[0-42]	5.37 (6.23)	6.15 (7.57)
Anxiety	[0-42]	5.00 (4.99)	4.58 (4.77)
Stress	[0-42]	8.59 (6.55)	8.55 (6.75)

Table 1) from the Dutch-speaking Flemish population. The sample size was assured to be higher than that in most previous studies that assessed the effects of (virtual) nature simulations on psychophysiological parameters (Browning et al., 2021; Browning, Mimnaugh, et al., 2020). No a priori power calculation was performed due to the complex interaction- and random effects and an initially unknown number of covariates (see section 2.8 Statistical analyses).

Participants were recruited through a media campaign that informed and attracted potential participants via a press release, website (‘*www.uitzicht.org*’), and Facebook page (‘*Uitzicht.onderzoek*’). Potential participants were informed about the goal and practicalities of the study but were blinded to the types of environments they could be exposed to during the experiment. They were also informed that there would be no financial compensation, but that in exchange for their participation, their personalized results would be shared with them privately after the experiment during an information session. The recruitment happened in three waves, each involving pre-selection and invitation (a flow chart of the participant recruitment is available in the supplementary materials section 1.1). The exclusion criteria were being pregnant, having a (chronic) disease of the heart (e.g., pacemaker), having a psychological/neurological/motor disorder or any other condition that prevents from functioning normally, taking medication for mental health (e.g., for stress), being sensitive to severe motion sickness, being visually or hearing impaired (including color blindness) even with corrective measures (e.g., through glasses, lenses or hearing aids), and having fears related to the environment (e.g., fear of water). All communication with the participants, including the questionnaires, was conducted in Dutch, the participants' native language.

Parameter	Levels or [Range]^{a}	N per level or Mean (SD)			X or F statistic^{b}	p
		Beach = Total N = 164	**Green N = 55**	**Urban N = 55**		
Design						
Period	First VR, Second VR	81, 83	28, 27	27, 28	1.35	0.51
Experiment location	Ghent, Ostend	128, 36	45, 10	40, 15	1.35	0.51
Sampling rate	512 Hz, 256 Hz	123, 41	43, 12	38, 17	1.35	0.51
Demographics						
Age	[18-65]	34.93 (13.23)	35.62 (13.94)	35.64 (13.45)	0.09	0.92
Sex	Male, Female	53, 111	17, 38	18, 37	1.35	0.51
SES	The same as my peers, Much better than my peers, Better than my peers, Worse than my peers, Much worse than my peers	96, 11, 42, 14, 1	29, 4, 15, 7, 0	37, 2, 14, 2, 0	1.35	0.51
Smoking status	Non-smoker, Former smoker, Smoker	137, 14, 13	44, 7, 4	47, 4, 4	1.35	0.51
BMI	[0-∞]	24.23 (4.12)	23.58 (3.36)	24.76 (4.52)	1.15	0.32
Civil status	Single, In a relationship, Living together, Married, Widow, Divorced	52, 43, 27, 37, 2, 3	19, 12, 10, 12, 0, 2	9, 20, 8, 16, 2, 0	1.35	0.51
Occupation	Student, Working, None	46, 113, 5	17, 37, 1	15, 36, 4	1.35	0.51
Net household income	<€1000/month, €1001-2000/month, €2001-3000/month, €3001-4000/month, €4001-5000/month, €5001-6000/month, >€6000/month	4, 26, 35, 29, 32, 20, 18	3, 7, 10, 13, 12, 2, 8	0, 6, 12, 9, 14, 9, 5	1.35	0.51
Physical activity level (IPAQ)	[0-∞]	2428.01 (3239.22)	2455.1 (2516.75)	2696.93 (4757.28)	0.13	0.88
Residential blue exposure	Every day, A lot, Moderately, Seldom, Never	12, 20, 27, 58, 8	4, 6, 10, 20, 3	5, 9, 9, 14, 6	1.35	0.51
Residential green exposure	Every day, A lot, Moderately, Seldom, Never	46, 59, 43, 16, 3	14, 24, 13, 6, 1	16, 18, 15, 4, 2	1.35	0.51
Residential coastal proximity	0-5km, >5-20km, >20-50km, >50-100km, >100km	14, 8, 64, 64, 14	4, 2, 21, 24, 4	4, 2, 22, 22, 5	1.35	0.51
DASS						
Depression	[0-42]	5.37 (6.23)	6.15 (7.57)	3.93 (4.71)	1.82	0.16
Anxiety	[0-42]	5.00 (4.99)	4.58 (4.77)	4.95 (5.09)	0.15	0.86

Stress	[0-42]	8.59 (6.55)	8.55 (6.75)	8.15 (6.6)	0.09	0.91

Table 1: Demographics table. The table depicts for each categorical parameter the factor levels and the number of participants per factor level and for each continuous parameter the range and mean and standard deviation per group (beach, green, or urban exposure).

Abbreviations: SES = socio-economic status; BMI = body-mass index; IPAQ = international physical activity questionnaire; DASS = depression, anxiety, and stress scale

[a] Ranges correspond to the theoretically possible minimum and maximum values.

[b] X statistic from a Chi-Square test for categorical variables. F statistic from an ANOVA for continuous predictors.

2.3 Virtual reality exposures

The virtual reality exposures were 16-minute 360° videos of Belgian beaches, inland urban spaces, and inland green spaces, each with their own ambient sound. Each video consisted of eight 2-minute scenes of these types of environments that transitioned by a 4-second fading to black at the end of the scene and a 4-second fading from black to the subsequent scene. The exposure of the beach showed scenes filmed at different proximities to the sea waterline to cover perspectives from all over the beach and with adjacent dunes or coastal towns; the exposure of the inland green spaces showed scenes of rural farmland, forests, and urban parks; and the exposure of the inland urban spaces showed scenes of city plazas, streets, and shopping areas (supplementary materials section 1.2). We consider these locations to be representative for what an individual might encounter during a recreational visit to either of these environments. Similar scenes were shown consecutively. All videos were shot at 5.6K at 30 fps with a 360° camera (GoPro MAX, 2019) mounted at eye level (150 to 160 cm from the ground) on a makeshift combination of tripods (Manfrotto 190, 2013; head replaced by the Three-Way Handle, GoPro, 2014). The camera operator sat in the vicinity of the tripod (10 to 20 meters) to record the sound with a professional shotgun-type microphone with a windshield (RØDE VideoMicro, 2010) that was mounted on a second handheld camera (the Nikon D850, 2017). The videos were shot under clement weather conditions on September 18th, 2020, May 31st, 2021, and June 16th, 2021. There were few visitors present in the environments at the time of filming. The scenes and sound recordings were cut and stitched together, and the tripod and camera operator were masked out with Premiere Pro (Adobe, 2021b) and After Effects (Adobe, 2021a). Figure 2 shows example frames from the scenes in the virtual reality videos. The videos were delivered to the participants through a head-mounted display (Oculus Rift S, 2019) and a noise-cancelling headphone (Sony WH-1000XM3, 2018).

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Beach

Green

Urban

Figure 2: Rectangular projection of spherical example frames from the virtual reality exposures. Scenes are chosen randomly from each exposure and solely serve illustrative purposes.

2.4 Physiological measurements

All autonomic and peripheral parameters were acquired with the NeXus-10 MKII and its accompanying sensors (Mind Media B.V., 2011). The protocol was set up and run in the accompanied software, BioTrace+ (version 2018A1; Mind Media B.V., 2020). The reference electrode was placed on the skin at the middle of the participants' left clavicle. More detailed descriptions of the physiological measurements are available in the supplementary materials section 1.3.

2.4.1 Heart rate and HF-HRV

The heart rate captured the overall level of arousal of the participant, and the HF-HRV was used as a proxy for parasympathetic nervous system activity (Berntson et al., 1997; Laborde et al., 2017; Malik et al., 1996; Shaffer & Ginsberg, 2017). Both were derived from an electrocardiogram according to standard guidelines (Laborde et al., 2017; Malik et al., 1996).

The raw signal was analyzed with the PhysioDataToolbox (v0.5.0; Sjak-Shie, 2019), which applied an ECG analyzer and a heart rate variability analyzer to the signal. For each 2-minute section of interest during baseline and exposure, the high frequency power (0.15-0.4 Hz, unit: ms^2) was used for further statistical analyses. Higher HF-HRV values indicate higher parasympathetic nervous system activity.

2.4.2 SCR

The SCR were used as a proxy for sympathetic nervous system activity. It was calculated from a skin conductance signal (Benedek & Kaernbach, 2010).

The raw signals were analyzed in Ledalab (V.3.4.8, Benedek and Kaernbach, 2015). For each 2-minute section of interest during baseline and exposure, the SCR was calculated as the average phasic driver (unit: muS) (Benedek & Kaernbach, 2010, 2015). Higher SCR values are reflective of higher sympathetic nervous system activity.

2.4.3 MAP

The MAP indicates the relative blood flow, which corresponds with many stress-related processes, including activation of autonomic, baro- and chemoreceptors, and endocrine mechanisms that regulate the cardiac output, arterial stiffness, and body temperature (Gopalan & Kirk, 2022). The signal was measured via photoplethysmography (i.e., by a blood volume pulse sensor; Mind Media B.V., 2011).

For each 2-minute section of interest during baseline and exposure, the MAP was extracted with the PhysioDataToolbox (v0.5.0; Sjak-Shie, 2019). For each detected systolic peak and diastolic valley, the MAP was calculated as the addition of the diastolic valley with one third of the difference between the diastolic valley and the systolic peak. Higher MAP values reflect higher blood pressure.

2.4.4 Breathing rate

The breathing rate is regulated by the respiratory center to maintain homeostatic blood parameters (e.g., oxygen depletion; Tipton et al., 2017). Conscious overriding is also possible. The breathing rate was retrieved from recordings of the inhalations and exhalations of the participants with a respiration belt (Mind Media B.V., 2011).

The signal was analyzed in BioTrace+ (version 2018A1, Mind Media B.V., 2020). The respiration rate was averaged for each 2-minute section of interest during baseline and exposure. Higher respiration rates are associated with (mal)adaptive coping with psychological and physiological stress (Tipton et al., 2017).

2.4.5 Muscle tone

Musculus trapezius pars descendens muscle tone reflects the electrical potential of the muscle, which is indicative for the input from the accessory nerve and the reticulospinal tract (Jensen et al., 1993; Johal et al., 2019). It was acquired via an electromyogram by placing a bipolar sensor of an ExG sensor (Mind Media B.V., 2011) along the midpoint of the lead line between the acromion and the spine of the 7th cervical vertebra according to standard guidelines (Jensen et al., 1993; Zipp, 1982).

The signal was analyzed in the PhysioDataToolbox (v0.5.0; Sjak-Shie, 2019). For each 2-minute section of interest during baseline and exposure, the mean value of the filtered, rectified, and smoothed signal was used for statistical analyses. Higher values indicate a higher innervation and a more tensed muscle.

2.5 Self-reported measurements

2.5.1 Positive and negative mood

The participants' positive and negative moods were assessed with the Dutch version of the Positive and Negative Affect Scale (PANAS; Engelen et al., 2006; Watson et al., 1988). This scale has been used extensively in similar previous research (Browning, Shipley, et al., 2020) and has been shown to have good construct validity (Crawford & Henry, 2004). The internal consistency in this study was good (Cronbach alpha positive mood = 0.92 and Cronbach alpha negative mood = 0.88). More details are available in the supplementary materials section 1.4.

2.5.2 Perceived stress

The perceived stress was measured with one question asking the participant "*How relaxed or stressed are you now?*", which was to be scored on an eleven-point Likert scale, with scores ranging from 0 (labelled "*Totally relaxed*"), over 5 (labelled "*Neutral*"), to 10 (labelled "*Totally stressed*"). Such single-item questionnaires have proven their reliability in the past (Verster et al., 2021).

2.5.3 Perceived quality of the environment for stress relief

The quality of the environment for stress relief as perceived by the participants was measured with a single question asking the participant "*At these places, I can relax*". Answers were to be scored on an eleven-point Likert scale with scores ranging from 0 (labelled "*Totally disagree*", over 5 (labelled "*Neutral*"), to 10 (labelled "*Totally agree*"). This type of questioning focuses on the likelihood of experiencing stress relief as determined by both retrospective and prospective imaginations (Hartig, 2011).

2.6 Stress level in the past week

The stress level in the past week was measured at the onset of the experiment with the stress subscale of the Dutch version of the Depression, Anxiety, and Stress Scale-21 (DASS-21; Lange, 2001). The seven items on the DASS stress subscale are hard to wind down, overreact, have nervous energy, get agitated, are difficult to relax, are intolerant, and are rather touchy, and these items have shown to have good scale reliability (Antony et al., 1998; Osman et al., 2012). The seven scores for stress were summed, multiplied by two, and further analyzed in their continuous formats. The internal consistency was good (Cronbach's alpha DASS-Stress = 0.85).

2.7 Covariates

A questionnaire was used in the online phase of the experiment to assess covariates related to the study design (e.g., order), demographics, environmental exposures, and personality. The covariates were the design period (i.e., the order), the experiment location, the sampling rate for physiological measurements, age, sex, socio-economic status (SES), smoking status, body mass index (BMI), civil status, occupation, net household income, level of physical activity (International Physical Activity Questionnaire; IPAQ), residential blue and green exposure, residential coastal proximity, and the DASS subscales of depression, anxiety, and stress.

2.8 Statistical analyses

The statistical analyses evaluated whether the changes in the physiological and self-reported parameters of stress differed between exposure to beaches vs. urban and green environments and whether these differences varied by level of stress in the past week.

One general linear mixed model was formulated for each physiological and self-reported measure of stress. The parameter of interest was included as sole outcome. Parameters that did not show a normal distribution on their histogram were transformed to a more satisfactory distribution: the negative mood, SCR, and muscle tone were square-root-transformed, and the HF-HRV was $\log^{10}$-transformed. The main predictor in the models was the triple interaction between the type of ‘environment’ (i.e., beach = reference, green, or urban), ‘stress level in the past week’ (continuous parameter), and ‘time’ (for the self-reports: pre = reference and post; for the physiology: b1 = reference, b2, e1, e2, e3, e4, e5, e6, e7, and e8). None of the covariates differed between the three environments (Table 1), so they were not included in the models. The mixed model structure included random intercepts and slopes to let the references and effect estimates vary for each participant and type of environment. To check the models’ assumption of normally distributed residuals, the modelled residuals over the fitted values were inspected visually. To check the models’ assumption of independent observations relative to the random effects, it was assessed whether the random effects variance was lower than the residual variance.

The unstandardized B-coefficients were extracted to assess the significance of differences from the reference category (i.e., beach, pre/b1) at $\alpha = 0.05$. The estimated marginal means were calculated for visualization. The estimated marginal means were computed for each level of the categorical predictors (i.e., ‘time’ and ‘environment’) and for two levels of stress in the past week: at the first and fourth quintiles, which indicate relatively ‘low’ (DASS-Stress = 2) and ‘moderate’ (DASS-Stress = 14) stress, respectively (Antony et al., 1998). The supplementary materials show the ANOVA estimates (section 2.1), the B-estimates with p-values corrected for the false discovery rate (section 2.2), the estimated marginal means with confidence intervals (section 2.3), and the differences between them (section 2.4). All analyses were performed in R (R Core Team, 2018), and the general linear mixed models were developed with the package *lme4* (Bates et al., 2015).

3 Results

3.1 Physiological parameters

Each virtual environment caused a lower heart rate and HF-HRV and a higher SCR, MAP, breathing rate, and muscle tone (Figure 3, Table 2). Beaches resulted in smaller increases in the breathing rate compared to the urban environments (e.g., $B_{\mathrm{Urban:e1}} = 1.926 \pm 0.879$, $p \leq 0.05$) and smaller increases in the SCR compared to the green environments (i.e., from e1 to e8; e.g., $B_{\mathrm{Green:e1}} = 0.083 \pm 0.032$, $p \leq 0.01$; Figure 3, Table 2). The smaller increases in the SCR were less pronounced when the level of stress in the past week was higher (e.g., $B_{\mathrm{Green:e1:DASS\text{-}Stress}} = -0.006 \pm 0.003$, $p \leq 0.05$). Urban environments resulted in intermediate SCR values.

The muscle tone showed complex patterns that were distinct per environment and per level of stress in the past week. More specifically, in the case of low levels of stress in the past week, beaches caused an increase in the upper trapezius muscle tone ($B_{\mathrm{e1}} = 0.014 \pm 0.005$, $p \leq 0.01$), and green environments did not (e.g., at $B_{\mathrm{Green:e1}} = -0.024 \pm 0.009$, $p \leq 0.01$). In the case of moderate levels of stress in the past week, beaches did not result in a higher upper trapezius muscle tone, but green environments did (e.g., at $B_{\mathrm{Green:e1:DASS\text{-}Stress}} = 0.003 \pm 0.001$, $p \leq 0.001$). These patterns occurred only during the first six minutes of the exposures.

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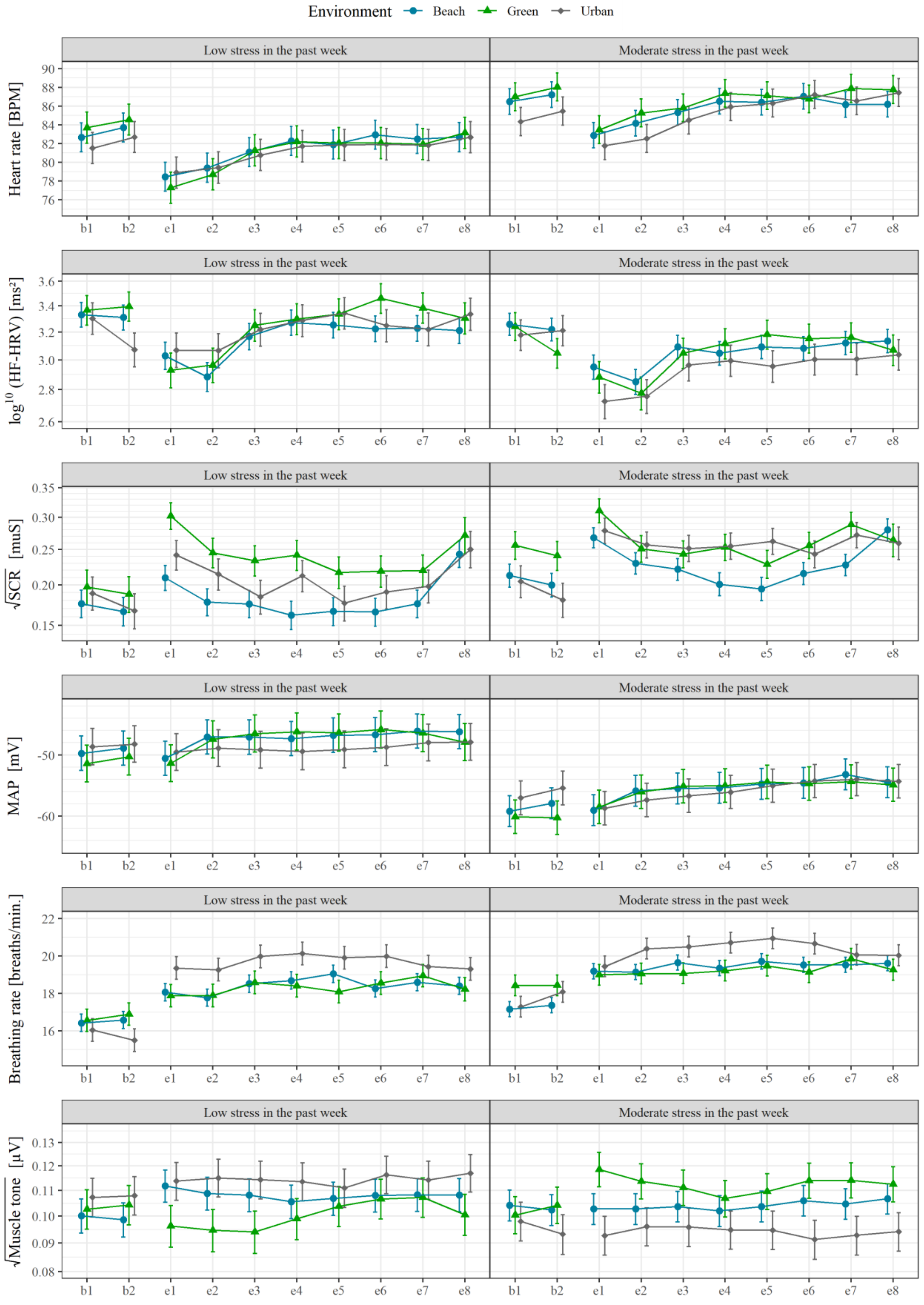

Figure 3: Visualized estimated marginal means and standard error of the physiological parameters of stress for each type of exposure (i.e., beach, green, and urban, see legend on top), and for participants who had a relatively 'low' and 'moderate' level of stress in the past week (i.e., DASS-Stress value at Q1 = 1 and at Q4 = 14, respectively). Significances of changes are

described in the main manuscript. Parameters that were transformed (i.e., HF-HRV, SCR, and Muscle tone) during modelling were not back-transformed for statistical accuracy. Abbreviations: HF-HRV = high frequency heart rate variability; SCR = skin conductance response; BPM = beats per minute; MAP = mean arterial pressure.

Coefficient	Heart rate N[a] = 2269 B ± SE		$\log^{10}$(HF-HRV) N[a] = 2218 B ± SE		√(SCR) N[a] = 2120 B ± SE		MAP N[a] = 2371 B ± SE		Breathing rate N[a] = 2445 B ± SE		√(Muscle tone) N[a] = 2322 B ± SE	
Intercept (Beach, b1)	82.034 ± 1.767	***	3.343 ± 0.110	***	0.170 ± 0.020	***	-48.142 ± 3.242	***	16.311 ± 0.533	***	0.099 ± 0.007	***
Green	1.116 ± 0.979		0.044 ± 0.110		0.018 ± 0.024		-1.820 ± 1.739		-0.063 ± 0.624		0.004 ± 0.007	
Urban	-0.979 ± 1.015		-0.021 ± 0.118		0.017 ± 0.022		0.875 ± 1.734		-0.460 ± 0.635		0.009 ± 0.007	
b2	1.110 ± 0.702		-0.017 ± 0.081		-0.009 ± 0.016		0.774 ± 1.220		0.145 ± 0.449		-0.001 ± 0.005	
e1	-4.330 ± 0.710	***	-0.300 ± 0.081	***	0.031 ± 0.015	*	-0.988 ± 1.230		1.569 ± 0.449	***	0.014 ± 0.005	**
e2	-3.401 ± 0.710	***	-0.453 ± 0.081	***	≤0.001 ± 0.015		2.549 ± 1.230	*	1.238 ± 0.449	**	0.010 ± 0.005	*
e3	-1.638 ± 0.710	*	-0.163 ± 0.081	*	-0.002 ± 0.015		2.456 ± 1.230	*	2.026 ± 0.449	***	0.009 ± 0.005	*
e4	-0.477 ± 0.710		-0.036 ± 0.081		-0.014 ± 0.015		2.161 ± 1.230	.	2.273 ± 0.449	***	0.007 ± 0.005	
e5	-0.880 ± 0.710		-0.064 ± 0.082		-0.008 ± 0.015		2.706 ± 1.230	*	2.628 ± 0.449	***	0.008 ± 0.005	.
e6	0.223 ± 0.710		-0.095 ± 0.082		-0.012 ± 0.015		2.770 ± 1.230	*	1.748 ± 0.449	***	0.009 ± 0.005	.
e7	-0.159 ± 0.710		-0.097 ± 0.082		-0.002 ± 0.016		3.222 ± 1.230	**	2.133 ± 0.450	***	0.009 ± 0.005	*
e8	0.062 ± 0.710		-0.118 ± 0.082		0.068 ± 0.019	***	3.303 ± 1.230	**	1.896 ± 0.452	***	0.009 ± 0.005	.
DASS-Stress	0.318 ± 0.154	*	-0.006 ± 0.010		0.003 ± 0.002	.	-0.790 ± 0.294	**	0.061 ± 0.048		≤0.001 ± 0.001	
Green:b2	-0.270 ± 1.347		0.083 ± 0.152		0.001 ± 0.033		0.585 ± 2.391		0.259 ± 0.863		0.003 ± 0.009	
Urban:b2	0.074 ± 1.400		-0.257 ± 0.163		-0.013 ± 0.030		-0.532 ± 2.395		-0.922 ± 0.879		0.003 ± 0.009	
Green:e1	-2.554 ± 1.378	.	-0.150 ± 0.155		0.083 ± 0.032	**	0.774 ± 2.444		-0.127 ± 0.863		-0.024 ± 0.009	**
Urban:e1	1.695 ± 1.412		0.105 ± 0.163		0.018 ± 0.030		0.240 ± 2.411		1.926 ± 0.879	*	-0.005 ± 0.009	
Green:e2	-2.133 ± 1.378		0.061 ± 0.155		0.057 ± 0.031	.	1.395 ± 2.444		0.214 ± 0.870		-0.022 ± 0.009	*
Urban:e2	1.269 ± 1.412		0.249 ± 0.163		0.021 ± 0.030		-2.766 ± 2.411		1.993 ± 0.879	*	-0.001 ± 0.009	
Green:e3	-0.996 ± 1.378		0.059 ± 0.155		0.046 ± 0.031		2.433 ± 2.444		0.228 ± 0.870		-0.021 ± 0.009	*
Urban:e3	0.740 ± 1.412		0.102 ± 0.164		-0.012 ± 0.030		-3.115 ± 2.411		2.013 ± 0.879	*	-0.001 ± 0.009	
Green:e4	-1.316 ± 1.378		-0.022 ± 0.156		0.066 ± 0.031	*	3.088 ± 2.444		-0.246 ± 0.870		-0.012 ± 0.009	
Urban:e4	0.438 ± 1.412		0.049 ± 0.164		0.033 ± 0.030		-3.202 ± 2.411		1.914 ± 0.879	*	0.001 ± 0.009	
Green:e5	-1.048 ± 1.378		0.037 ± 0.155		0.035 ± 0.031		2.253 ± 2.444		-1.009 ± 0.870		-0.008 ± 0.009	

Urban:e5	0.927 ± 1.412		0.150 ± 0.164		-0.016 ± 0.030		-3.545 ± 2.411		1.252 ± 0.879		-0.003 ± 0.009	
Green:e6	-2.093 ± 1.378		0.219 ± 0.155		0.037 ± 0.031		2.814 ± 2.444		0.470 ± 0.870		-0.006 ± 0.009	
Urban:e6	-0.233 ± 1.412		0.061 ± 0.164		0.008 ± 0.030		-3.310 ± 2.411		2.275 ± 0.879	**	0.003 ± 0.009	
Green:e7	-2.046 ± 1.381		0.130 ± 0.156		0.023 ± 0.032		1.632 ± 2.444		0.418 ± 0.870		-0.006 ± 0.009	
Urban:e7	0.146 ± 1.412		0.031 ± 0.164		0.002 ± 0.030		-2.917 ± 2.411		1.348 ± 0.879		≤0.001 ± 0.009	
Green:e8	-0.837 ± 1.390		0.074 ± 0.157		0.017 ± 0.039		-0.076 ± 2.460		-0.093 ± 0.885		-0.013 ± 0.009	
Urban:e8	0.775 ± 1.412		0.182 ± 0.166		-0.005 ± 0.037		-2.843 ± 2.411		1.440 ± 0.881		0.003 ± 0.009	
Green:DASS-Stress	-0.043 ± 0.090		-0.004 ± 0.010		0.002 ± 0.002		0.064 ± 0.160		0.095 ± 0.058		-0.001 ± 0.001	
Urban:DASS-Stress	-0.083 ± 0.096		-0.004 ± 0.011		-0.002 ± 0.002		0.094 ± 0.168		0.042 ± 0.059		-0.001 ± 0.001	.
b2:DASS-Stress	-0.026 ± 0.063		-0.002 ± 0.007		≤0.001 ± 0.001		0.037 ± 0.112		0.005 ± 0.041		≤0.001 ± ≤0.001	
e1:DASS-Stress	0.053 ± 0.063		≤0.001 ± 0.007		0.002 ± 0.001		0.081 ± 0.112		0.032 ± 0.041		-0.001 ± ≤0.001	**
e2:DASS-Stress	0.077 ± 0.063		0.003 ± 0.007		0.001 ± 0.001		0.056 ± 0.112		0.053 ± 0.041		-0.001 ± ≤0.001	*
e3:DASS-Stress	0.036 ± 0.063		≤0.001 ± 0.007		0.001 ± 0.001		0.090 ± 0.112		0.033 ± 0.041		-0.001 ± ≤0.001	.
e4:DASS-Stress	0.037 ± 0.063		-0.013 ± 0.007	.	≤0.001 ± 0.001		0.117 ± 0.112		-0.006 ± 0.041		-0.001 ± ≤0.001	
e5:DASS-Stress	0.058 ± 0.063		-0.007 ± 0.007		-0.001 ± 0.001		0.125 ± 0.112		-0.006 ± 0.041		-0.001 ± ≤0.001	
e6:DASS-Stress	0.025 ± 0.063		-0.006 ± 0.007		0.001 ± 0.001		0.132 ± 0.112		0.044 ± 0.041		-0.001 ± ≤0.001	
e7:DASS-Stress	-0.012 ± 0.063		-0.003 ± 0.007		0.001 ± 0.001		0.200 ± 0.112	.	0.016 ± 0.041		-0.001 ± ≤0.001	
e8:DASS-Stress	-0.024 ± 0.063		≤0.001 ± 0.007		≤0.001 ± 0.002		0.103 ± 0.112		0.039 ± 0.041		≤0.001 ± ≤0.001	
Green:b2:DASS-Stress	0.041 ± 0.123		-0.017 ± 0.014		≤0.001 ± 0.003		-0.144 ± 0.220		-0.033 ± 0.080		≤0.001 ± 0.001	
Urban:b2:DASS-Stress	0.022 ± 0.132		0.024 ± 0.016		≤0.001 ± 0.003		0.060 ± 0.232		0.108 ± 0.081		≤0.001 ± 0.001	
Green:e1:DASS-Stress	0.188 ± 0.125		0.007 ± 0.014		-0.006 ± 0.003	*	0.050 ± 0.223		-0.095 ± 0.080		0.003 ± 0.001	***
Urban:e1:DASS-Stress	-0.048 ± 0.130		-0.018 ± 0.015		≤0.001 ± 0.003		-0.149 ± 0.228		-0.128 ± 0.081		≤0.001 ± 0.001	
Green:e2:DASS-Stress	0.195 ± 0.125		-0.008 ± 0.014		-0.006 ± 0.003	*	-0.045 ± 0.223		-0.111 ± 0.080		0.003 ± 0.001	**
Urban:e2:DASS-Stress	-0.054 ± 0.130		-0.019 ± 0.015		0.001 ± 0.003		-0.066 ± 0.228		-0.062 ± 0.081		≤0.001 ± 0.001	
Green:e3:DASS-Stress	0.068 ± 0.125		-0.006 ± 0.014		-0.005 ± 0.003	.	-0.082 ± 0.223		-0.147 ± 0.080	.	0.002 ± 0.001	**
Urban:e3:DASS-Stress	0.040 ± 0.130		-0.011 ± 0.015		0.004 ± 0.003		-0.019 ± 0.228		-0.092 ± 0.081		≤0.001 ± 0.001	
Green:e4:DASS-Stress	0.117 ± 0.125		0.008 ± 0.014		-0.004 ± 0.003		-0.127 ± 0.223		-0.082 ± 0.080		0.001 ± 0.001	.
Urban:e4:DASS-Stress	0.080 ± 0.130		-0.001 ± 0.015		0.002 ± 0.003		0.025 ± 0.228		-0.048 ± 0.081		≤0.001 ± 0.001	

Green:e5:DASS-Stress	0.088 ± 0.125		0.005 ± 0.014		-0.003 ± 0.003		-0.073 ± 0.223		-0.035 ± 0.080		0.001 ± 0.001	
Urban:e5:DASS-Stress	0.079 ± 0.130		-0.015 ± 0.015		0.007 ± 0.003	*	0.076 ± 0.228		-0.010 ± 0.081		≤0.001 ± 0.001	
Green:e6:DASS-Stress	0.092 ± 0.125		-0.009 ± 0.014		-0.003 ± 0.003		-0.142 ± 0.223		-0.152 ± 0.080	.	0.001 ± 0.001	
Urban:e6:DASS-Stress	0.183 ± 0.130		-0.004 ± 0.015		0.002 ± 0.003		0.102 ± 0.228		-0.090 ± 0.081		-0.001 ± 0.001	
Green:e7:DASS-Stress	0.232 ± 0.127	.	-0.005 ± 0.014		≤0.001 ± 0.003		-0.136 ± 0.223		-0.097 ± 0.080		0.001 ± 0.001	.
Urban:e7:DASS-Stress	0.171 ± 0.130		-0.005 ± 0.015		0.004 ± 0.003		-0.004 ± 0.228		-0.067 ± 0.081		≤0.001 ± 0.001	
Green:e8:DASS-Stress	0.134 ± 0.127		-0.009 ± 0.014		-0.005 ± 0.003		0.041 ± 0.223		-0.109 ± 0.081		0.002 ± 0.001	*
Urban:e8:DASS-Stress	0.185 ± 0.130		-0.014 ± 0.016		≤0.001 ± 0.003		0.056 ± 0.228		-0.081 ± 0.081		-0.001 ± 0.001	

Table 2: B-coefficients and standard errors (SE) of the physiological parameters of stress from the general linear mixed models. Each column depicts the results from the model on that outcome parameter. The intercepts represent the predicted values of the outcome parameter for the beach at b1 at the mean value of DASS-Stress (continuous variable). The B-coefficients of the categorical main effects (i.e., 'green', 'urban', 'b2', and 'e1' to 'e8') indicate the changes from the intercept to these predictor levels, and those of the continuous main effects (i.e., 'DASS-Stress') indicate their slopes, while all other predictors are held constant. The B-coefficients of the interaction terms (i.e., those with ':') indicate the changes from the intercept (i.e., for categorical predictors) or slopes (i.e., for those with DASS-Stress) above those of the main effects. As such, all coefficients are relative to the effects of the 'beach'. B-coefficients are unstandardized.

Significances: '.': $p \leq 0.1$; '': $p \leq 0.05$; '**': $p \leq 0.01$; '***': $p \leq 0.001$.*

Abbreviations: HF-HRV = high frequency heart rate variability; SCR = skin conductance response; MAP = mean arterial pressure.

[a] N-values represent the number of individual observations or data points on which the model was based.

3.2 Self-reported parameters

Beaches scored better than urban environments on all of the measured self-reported parameters of stress. More specifically, beaches decreased the negative mood and perceived stress under moderate levels of stress in the past week ($B_{Post:DASS\text{-}Stress} = -0.009 \pm 0.003$, $p \leq 0.01$), while the urban environments increased these parameters under both low and moderate stress in the past week (Figure 4, Table 3), and the green environments did not impact these parameters under moderate stress in the past week. The positive mood decreased in response to urban environments under moderate levels of stress in the past week ($B_{Urban:Post:DASS\text{-}Stress} = -0.036 \pm 0.012$, $p \leq 0.01$) and urban environments showed a much lower perceived quality for relaxation than beaches and green environments ($B_{Urban} = -4.5 \pm 0.5$, $p \leq 0.001$). Generally, participants with a higher stress level in the past week displayed worse scores for positive mood, negative mood, and perceived stress.

Please display Figure 4 in color online and in color in print. Please print this figure fitting 1 column.

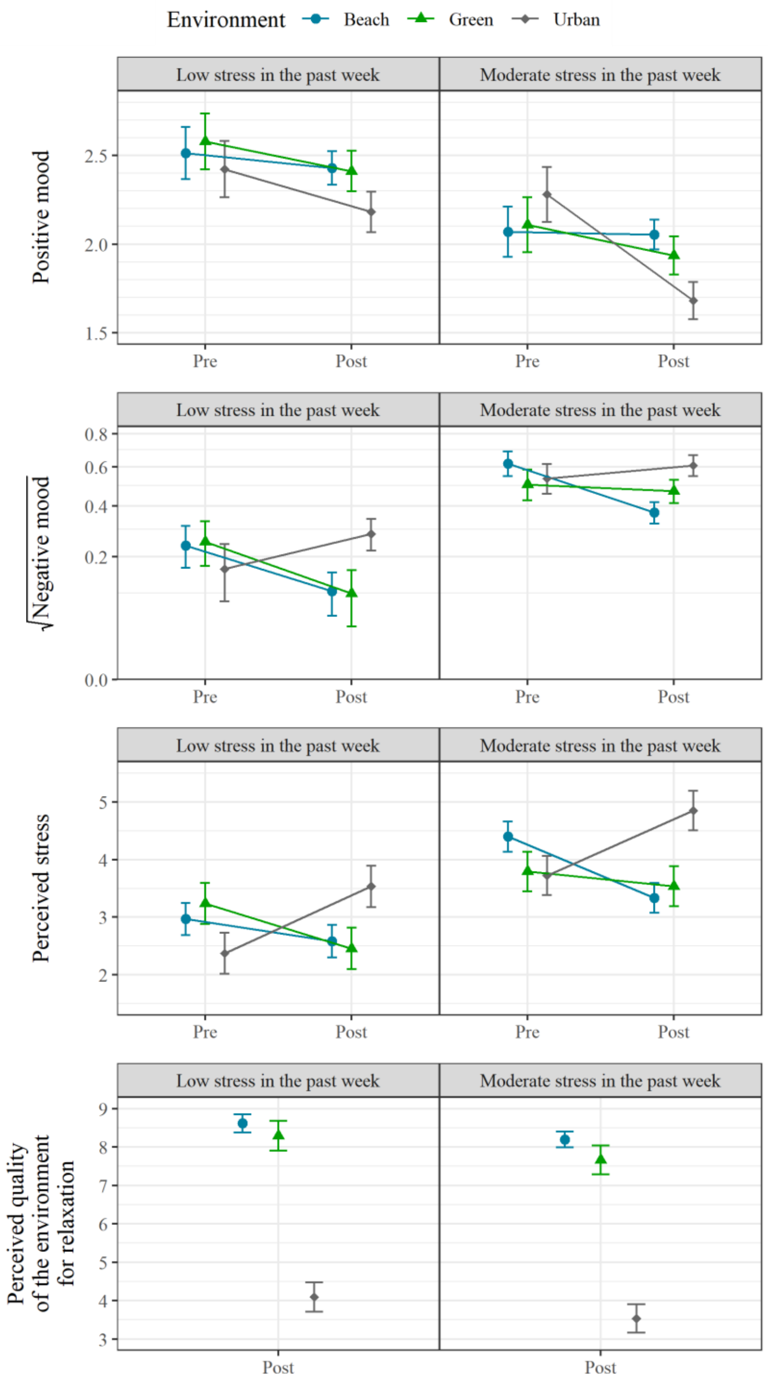

Figure 4: Visualized estimated marginal means and standard errors of the self-reported parameters of stress for each type of exposure (i.e., beach, green, and urban, see legend on top), and for participants who had a relatively 'low' (DASS-Stress value at Q1 = 1) and 'moderate' (DASS-Stress value at Q4 = 14) level of stress in the past week. Significances of changes are described in the main manuscript. Parameters that were transformed during modelling (i.e., negative mood) are plotted with their transformed values on the transformed axes.

Table 3: B-coefficients and standard errors (SE) of the self-reported parameters of stress from the general linear mixed models. Each column depicts the results from the model on that parameter. The intercepts represent the predicted values of the outcome parameter for the beach before the exposure ('pre') at the mean value of DASS-Stress (continuous variable). The B-coefficients of the categorical main effects (i.e., 'green', 'urban', and 'post') indicate the changes from the intercept to these predictor levels, and those of the continuous main effects (i.e., 'DASS-Stress') indicate their slopes, while all other predictors are held constant. The B-coefficients of the interaction terms (i.e., those with ':') indicate the changes from the intercept (categorical predictors only) or slopes (i.e., with DASS-Stress) above those of the main effects. As such, all coefficients are relative to the effects of the 'beach'. B-coefficients are unstandardized.
Significances: '.': p ≤ 0.1; '': p ≤ 0.05; '**': p ≤ 0.01; '***': p ≤ 0.001.*
^{a} N-values represent the number of individual observations or data points on which the model was based.

	Positive mood		√(Negative mood)		Perceived stress		Perceived quality of the environment for relaxation	
	N^a = 541		N^a = 541		N^a = 541		N^a = 269	
Coefficient	B ± SE		B ± SE		B ± SE		B ± SE	
Intercept (Beach, Pre)	2.588 ± 0.154	**	0.176 ± 0.076		2.732 ± 0.305	***	8.685 ± 0.266	***
Green	0.069 ± 0.095		0.034 ± 0.055		0.415 ± 0.347		-0.285 ± 0.495	
Urban	-0.142 ± 0.095		-0.076 ± 0.055		-0.583 ± 0.351	.	-4.497 ± 0.504	***
Post	-0.097 ± 0.122		-0.117 ± 0.047	.	-0.273 ± 0.237		/	
DASS-Stress	-0.037 ± 0.008	***	0.032 ± 0.004	***	0.119 ± 0.023	***	-0.035 ± 0.024	
Green:Post	-0.069 ± 0.123		-0.057 ± 0.071		-0.597 ± 0.452		/	
Urban:Post	-0.084 ± 0.124		0.243 ± 0.072	***	1.440 ± 0.460	**	/	
Green:DASS-Stress	-0.002 ± 0.009		-0.011 ± 0.005	*	-0.073 ± 0.033	*	-0.018 ± 0.046	
Urban:DASS-Stress	0.025 ± 0.009	**	-0.001 ± 0.005		-0.006 ± 0.033		-0.012 ± 0.047	
Post:DASS-Stress	0.006 ± 0.006		-0.009 ± 0.003	**	-0.057 ± 0.022	**	/	
Green:Post:DASS-Stress	-0.006 ± 0.011		0.019 ± 0.007	**	0.100 ± 0.042	*	/	
Urban:Post:DASS-Stress	-0.036 ± 0.012	**	0.006 ± 0.007		0.054 ± 0.043		/	

4 Discussion

4.1 Main results

The results of this study demonstrate that beaches are more effective than urban and green environments in relaxing the physiological pathways of stress. First and foremost, beaches induced a lower increase in the breathing rate than urban environments. To our knowledge, no previous study has compared the effects of beaches and urban environments on the physiology of breathing. Importantly, breathing unconsciously is regulated by both the sympathetic and parasympathetic nervous systems' activity to maintain homeostatic blood parameters (e.g., prevent oxygen depletion; Tipton et al., 2017). Inversely, breathing slower also influences respiratory, cardiovascular, autonomic, cognitive, and emotional processes that can have far-reaching benefits for health (see Russo et al., 2017, and Zaccaro et al., 2018, for the full range of benefits). Thus, the fact that many people who are exposed to beaches report benefits for health and wellbeing may be caused by these people relatively slowing down their breathing (Ashbullby et al., 2013; Bell et al., 2015; Hipp & Ogunseitan, 2011; Hooyberg et al., 2022; Peng et al., 2016b, 2016a; Severin et al., 2022; White et al., 2010; Wyles et al., 2016). Noteworthy is that these benefits of beaches did not differ from the effects of green environments.

The results of this study strengthen the evidence from the literature that shows that beaches downregulate the sympathetic nervous system, and have no influence on the parasympathetic nervous system or the overall cardiovascular arousal. More specifically, Anderson et al. (2017) found that watching virtual remote beaches decreased skin conductance levels more than the urban control, indicating that beaches downregulate the sympathetic nervous system activity. From our visualizations, it also seemed that beaches had a more downregulating force on the SCR relative to urban environments, but these differences were not statistically significant, unfortunately. The parasympathetic responses to beaches seem to be negligible, because our study and previous studies found that the HF-HRV responses to beaches vs. urban environments did not differ (Anderson et al., 2017; Triguero-Mas et al., 2017; White et al., 2015).[2] Apparently, beaches also do not decrease the overall cardiovascular arousal, because neither this study nor previous studies found changes in the heart rate or MAP (Anderson et al., 2017; Triguero-Mas et al., 2017; Vert et al., 2020; White et al., 2015).

To our knowledge, this is also the first study that analytically compares the effects of beaches with those of green environments on physiological outcomes. Most strikingly, beaches caused smaller increases in SCR than green environments, meaning that beaches seem to be more efficient in calming the central nervous system in driving the sudomotor activity of the sympathetic nervous system (Christopoulos et al., 2019; Laborde et al., 2017). This effect was less pronounced under moderate stress, potentially because participants with moderate stress already had high SCR. As such, the large increase in response to green environments was limited due to a ceiling effect, while the smaller increase in response to beaches was not (Figure 3). Also meaningful was the fact that beaches decreased the negative mood and perceived stress under both low and moderate stress, but green exposures only reduced these parameters under low stress. Crucially, this suggests that people who had a moderate stress level in the past week would rather benefit from a (virtual) exposure to a beach

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[2] Note that some of these studies used the low-frequency to high-frequency heart rate variability ratio (LF/HF) as an index of the autonomic balance or the relative power of the sympathetic over the parasympathetic nervous system activity (Triguero-Mas et al., 2017; Vert et al., 2020). However, using the LF/HF ratio as an index for the autonomic balance has been contested (Billman, 2013). So, we did not calculate these indices in this study nor do we make inferences from these measures when interpreting the results of these studies, and we focus on those indices that reflect the pure parasympathetic (i.e., HF-HRV) or pure sympathetic (i.e., SCR) nervous system activity (Benedek & Kaernbach, 2010; Berntson et al., 1997; Laborde et al., 2017; Laine et al., 2009; Malik et al., 1996).

than a green environment. A final, but less explicable, result was that the upper trapezius muscle tone increased in response to beaches under low but not moderate stress, while green environments increased the upper trapezius muscle tone under moderate but not low stress. During involuntary contraction, the upper trapezius muscle tone displays the activity of the accessory nerve (i.e., the eleventh cranial nerve) and the reticulospinal tract, which is responsible for locomotion and postural movement (Johal et al., 2019; Marker et al., 2017; Paulsen & Waschke, 2011). A higher muscle tone is generally associated with more mental stress (Marker et al., 2017; Wijsman et al., 2013). Previous studies that evaluated the effects of nature on muscle tone have always focused on the frontalis muscle on the forehead, which became less tensed in response to green exposures (Largo-Wight et al., 2016; Ulrich et al., 1991). Given the complexity of our results and the absence of any previous studies on upper trapezius muscle responses to beaches, we argue that further research is necessary to disentangle how somatic excitations, such as those of the upper trapezius or frontalis muscles, may differ depending on the type of exposed environment and the stress-level of the exposed individual. In sum, each of the many visual and auditory features that are unique to beaches may have contributed to their beneficial effects on the breathing rate, sympathetic nervous system activity, and subjective ratings of stress and mood (e.g., presence of sand, sky visibility, colors; Cracknell, 2019; Hooyberg et al., 2022).

4.2 Limitations and strengths

This study is unique compared to the previous literature, because no previous study has assessed both cardiovascular, respiratory, and muscular pathways of stress in response to beaches, while making the comparison with urban and green environments and while considering the level of stress in the past week. We also deviated from the convention of considering the urban exposure as the control (Browning et al., 2021; Hartig et al., 2014). Instead, we considered the beach as the control to have all our participants exposed to the environment of prime interest and to result in maximal power for the comparison with both the urban and green environments.

This study exploited the natural variation of stress in the past week from a relatively large and representative sample (N = 164), which allowed us to gain societally relevant insights. A potential downside of this is that the recruited participants also had divergent demographic and health characteristics, which may have resulted in relatively large uncertainties on the estimated effect sizes compared to when a more confined population would have been sampled. Since there were few participants who reported a 'high' level of stress in the previous week, the visualizations of our analyses were restricted to 'low' and 'moderate' levels of precedent stress. Nevertheless, the acquired data revealed that the effects of beaches and green spaces differ when the level of precedent stress increases, and that the self-reported benefits of green environments did not hold under moderate levels of precedent stress.

The use of virtual reality has led to consistent physiological reactions at the onset of the exposures. At the start of the virtual reality exposures, there was an apparent downregulation of the parasympathetic nervous system and an upregulation of the sympathetic nervous system. The use of virtual reality may also have caused beaches not to improve the positive mood (see Browning, Mimnaugh, et al., 2020 for the reasons why; Browning, Shipley, et al., 2020; Elliott et al., 2015, 2018; Hooyberg et al., 2022; White et al., 2010, 2014, 2020; Wyles et al., 2016). Also, it seems that the 16-minute virtual reality exposures used in this study did not provide additional benefits over the often used shorter exposures of 10 minutes (Browning, Mimnaugh, et al., 2020; Calogiuri & Elliott, 2017; Chirico & Gaggioli, 2019). From 12 minutes onwards, there was even heightened sympathetic activity, which potentially reflected feelings of frustration, agitation, and impatience towards the end. Nevertheless, virtual reality still proved to be a valuable tool for exposing the large number of participants to the different environments while blinding them to the environment they were going to be exposed to. It also ensured a higher level of immersion compared to alternative flat-screen-type exposures and excluded the undesired effects of physical activity and sensory inputs otherwise found in real environments (Anderson et al., 2017; Browning et al., 2021; Browning, Mimnaugh, et al., 2020).

4.3 Avenues for future research

To expand the knowledge base on the effects of beaches, future research should replicate the results of this study on different populations and in different contexts (e.g., not with virtual reality), while tackling the limitations of this study and drawing from its strengths. While doing so, it is crucial to measure indices of both parasympathetic, sympathetic, and somatic physiological pathways, because the results of this study show that measuring only one of these may lead to incomplete interpretations. Furthermore, a number of new avenues for future research seem societally and scientifically relevant. Firstly, since stress-reduction theory and attention restoration theory predict that emotional responses to outdoor environments should coincide with cognitive changes (Kaplan & Kaplan, 1989; Ulrich et al., 1991), future research should test the effects of coastal environments also on cognitive performance, brain functioning, (visual) attention, and neurological and hormonal processes in the brain. While this study mainly focused on autonomically and somatically driven changes, understanding the full stress-reactivity to beaches will also require measurements of the hypothalamic–pituitary–adrenal axis, such as cortisol. Additionally, there exist many types of coastal environments that differ in perceived restorativeness (Hooyberg et al., 2022), and future research should validate whether those differences also translate into different psychophysiological reactions. Some coastal environments may also attract different visitors with different habitus, and disentangling the sociological variation behind these visits might help to explain why some people may benefit more or less from the coast and specific coastal environments than others. In this respect, the moderating effects of other pathologies than perceived levels of stress in the past week should be assessed, and those that drive the most differential effects should be identified. For example, the benefits of the coast may differ depending on the severity of personality traits, symptoms of anxiety, depression, rumination, or burnout, or even beliefs about the health benefits of the coast. Interestingly, the acquired data for this study allows to perform additional analyses on character-specific responses to the exposed environments other than the stress level in the past week (i.e., by age, gender, or socio-economic status).

5 Conclusion

This study strengthens the evidence about how beaches impact physiological and self-reported parameters of stress differently than urban and green environments. We demonstrate that beaches slow down the breathing rate more than urban environments and downregulate the sympathetic nervous system more than green environments. The effects of beaches on the heart rate, HF-HRV, and MAP were negligible, which adds to a consistent pattern in the extant literature (Anderson et al., 2017; Triguero-Mas et al., 2017; Vert et al., 2020; White et al., 2015). The upper trapezius muscle tone reacted differently to beaches and green environments depending on the stress level in the past week. Beaches reduced the negative mood (not positive mood) and self-rated stress under moderate levels of initial stress, while green environments did not improve these parameters under moderate stress, and urban environments relatively worsened all self-reported parameters of stress. Overall, the results of this study illustrate that exposure to (virtual) beaches improves health and wellbeing by providing psychological and physiological restoration. Future research should focus on further strengthening the evidence base by replicating this study's results and testing the effects on populations with different socio-demographic and health characteristics and with different modes of exposure.

6 Competing interests

The authors declare no actual or potential conflicts of interests.

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Declarations of interest: none

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9 CRediT statement

Alexander Hooyberg: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing – Original Draft, Writing – Review & Editing, Visualization, Project administration; **Nathalie Michels:** Conceptualization, Methodology, Writing – Review and Editing, Supervision, Project administration; **Henk Roose:** Conceptualization, Methodology, Writing – Review and Editing, Supervision, Project administration; **Gert Everaert:** Conceptualization, Methodology, Writing – Review and Editing, Supervision, Project administration, Funding acquisition; **Ilias Mokas:** Conceptualization, Methodology; **Robert Malina:** Conceptualization, Methodology, Writing – Review and Editing; **Marie-Anne Vanderhasselt:** Conceptualization, Methodology, Writing – Review and Editing; **Stefaan De Henauw:** Conceptualization, Methodology, Writing – Review and Editing, Supervision, Project administration

10 Supplementary information

Supplementary data associated with this article can be found in the online version.

11 Role of the funding source

The funding source was not involved in this study.

12 References

Adobe. (2021a). *After Effects [Computer software]* (18.0). Adobe.

Adobe. (2021b). *Premiere Pro [Computer software]* (14.9). Adobe.

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. *Aerospace Medicine and Human Performance*, *88*(6), 520–526. https://doi.org/10.3357/AMHP.4747.2017

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. https://doi.org/10.1016/j.physbeh.2013.05.023

Antony, M. M., Cox, B. J., Enns, M. W., Bieling, P. J., & Swinson, R. P. (1998). Psychometric properties of the 42-item and 21-item versions of the Depression Anxiety Stress Scales in clinical groups and a community sample. *Psychological Assessment*, *10*(2), 176–181. https://doi.org/10.1037/1040-3590.10.2.176

Ashbullby, K. J., Pahl, S., Webley, P., & White, M. P. (2013). The beach as a setting for families' health promotion: A qualitative study with parents and children living in coastal regions in Southwest England. *Health & Place*, *23*, 138–147. https://doi.org/10.1016/j.healthplace.2013.06.005

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software*, *67*(1), 1–48. https://doi.org/10.18637/jss.v067.i01

Bell, S. L., Phoenix, C., Lovell, R., & Wheeler, B. W. (2015). Seeking everyday wellbeing: The coast as a therapeutic landscape. *Social Science and Medicine*, *142*, 56–67. https://doi.org/10.1016/j.socscimed.2015.08.011

Benedek, M., & Kaernbach, C. (2010). A continuous measure of phasic electrodermal activity. *Journal of Neuroscience Methods*, *190*(1), 80–91. https://doi.org/10.1016/j.jneumeth.2010.04.028

Benedek, M., & Kaernbach, C. (2015). *Ledalab*. www.ledalab.de

Berntson, G. G., Thomas Bigger, J., Eckberg, D. L., Grossman, P., Kaufmann, P. G., Malik, M., Nagaraja, H. N., Porges, S. W., Saul, J. P., Stone, P. H., & Van Der Molen, M. W. (1997). Heart rate variability: Origins methods, and interpretive caveats. *Psychophysiology*, *34*(6), 623–648. https://doi.org/10.1111/j.1469-8986.1997.tb02140.x

Berto, R. (2014). The Role of Nature in Coping with Psycho-Physiological Stress: A Literature Review on Restorativeness. *Behavioral Sciences*, *4*(4), 394–409. https://doi.org/10.3390/bs4040394

Billman, G. E. (2013). The LF/HF ratio does not accurately measure cardiac sympatho-vagal balance. *Frontiers in Physiology*, *4 FEB*(February), 1–5. https://doi.org/10.3389/fphys.2013.00026

Block, J. D., & Bridger, W. H. (1962). The Law of Initial Value in Psychophysiology: A Reformulation in Terms of Experimental and Theoretical Considerations. *Annals of the New York Academy of Sciences*, *98*(4), 1229–1241. https://doi.org/10.1111/j.1749-6632.1962.tb30631.x

Browning, M. H. E. M., Mimnaugh, K. J., van Riper, C. J., Laurent, H. K., & LaValle, S. M. (2020). Can Simulated Nature Support Mental Health? Comparing Short, Single-Doses of 360-Degree Nature Videos in Virtual Reality With the Outdoors. *Frontiers in Psychology*, *10*(January), 001391652090648. https://doi.org/10.3389/fpsyg.2019.02667

Browning, M. H. E. M., Saeidi-Rizi, F., McAnirlin, O., Yoon, H., & Pei, Y. (2021). The Role of Methodological Choices in the Effects of Experimental Exposure to Simulated Natural Landscapes on Human Health and Cognitive Performance: A Systematic Review. *Environment and Behavior*, *53*(7), 687–731. https://doi.org/10.1177/0013916520906481

Browning, M. H. E. M., Shipley, N., McAnirlin, O., Becker, D., Yu, C. P., Hartig, T., & Dzhambov, A. M. (2020). An Actual Natural Setting Improves Mood Better Than Its Virtual Counterpart: A Meta-Analysis of Experimental Data. In *Frontiers in Psychology* (Vol. 11, Issue September, pp. 1–12). https://doi.org/10.3389/fpsyg.2020.02200

Cacioppo, J. T., Tassinary, L. G., & Berntson, G. G. (2007). *The Handbook of Psychophysiology* (3rd ed.). Cambridge University Press. www.cambridge.org/9780521844710

Calogiuri, G., & Elliott, L. R. (2017). Why do people exercise in natural environments? Norwegian adults' motives for nature-, gym-, and sports-based exercise. *International Journal of Environmental Research and Public Health*, *14*(4). https://doi.org/10.3390/ijerph14040377

Cardinali, D. P. (2018). *Autonomic Nervous System*. Springer International Publishing. https://doi.org/10.1007/978-3-319-57571-1

Chirico, A., & Gaggioli, A. (2019). When Virtual Feels Real: Comparing Emotional Responses and

Presence in Virtual and Natural Environments. *Cyberpsychology, Behavior, and Social Networking*, *22*(3), 220–226. https://doi.org/10.1089/cyber.2018.0393

Christopoulos, G. I., Uy, M. A., & Yap, W. J. (2019). The Body and the Brain: Measuring Skin Conductance Responses to Understand the Emotional Experience. *Organizational Research Methods*, *22*(1), 394–420. https://doi.org/10.1177/1094428116681073

Chrousos, G. P. (2009). Stress and disorders of the stress system. *Nature Reviews Endocrinology*, *5*(7), 374–381. https://doi.org/10.1038/nrendo.2009.106

Corazon, S. S., Sidenius, U., Poulsen, D. V., Gramkow, M. C., & Stigsdotter, U. K. (2019). Psycho-physiological stress recovery in outdoor nature-based interventions: A systematic review of the past eight years of research. *International Journal of Environmental Research and Public Health*, *16*(10). https://doi.org/10.3390/ijerph16101711

Cracknell, D. (2019). *By the Sea: The therapeutic benefits of being in, on and by the water*. Aster.

Crawford, J. R., & Henry, J. D. (2004). The Positive and Negative Affect Schedule (PANAS): Construct validity, measurement properties and normative data in a large non-clinical sample. *British Journal of Clinical Psychology*, *43*(3), 245–265. https://doi.org/10.1348/0144665031752934

Dahn, J. R., & And, F. J. P. (2005). Exercise and well-being: a review of mental and physical health benefits associated with physical activity. *Current Opinion in Psychiatry*, *18*(2), 189–193. http://content.wkhealth.com/linkback/openurl?sid=WKPTLP:landingpage&an=00001504-200503000-00013

Elliott, L. R., White, M. P., Grellier, J., Rees, S. E., Waters, R. D., & Fleming, L. E. (2018). Recreational visits to marine and coastal environments in England: Where, what, who, why, and when? *Marine Policy*, *97*(February), 305–314. https://doi.org/10.1016/j.marpol.2018.03.013

Elliott, L. R., White, M. P., Taylor, A. H., & Herbert, S. (2015). Energy expenditure on recreational visits to different natural environments. *Social Science and Medicine*, *139*, 53–60. https://doi.org/10.1016/j.socscimed.2015.06.038

Engelen, U., Peuter, S. De, Victoir, A., Diest, I. Van, & Van den Bergh, O. (2006). Verdere validering van de Positive and Negative Affect Schedule (PANAS) en vergelijking van twee Nederlandstalige versies. *Gedrag En Gezondheid*, *34*(2), 61–70. https://doi.org/10.1007/bf03087979

Eurostat. (2022). *Nights spent at tourist accommodation establishments by coastal and non-coastal area (from 2012 onwards) in the EU27_2020*.

Frumkin, H., Bratman, G. N., Breslow, S. J., Cochran, B., Kahn, P. H., Lawler, J. J., Levin, P. S., Tandon, P. S., Varanasi, U., Wolf, K. L., & Wood, S. A. (2017). Nature contact and human health: A research agenda. In *Environmental Health Perspectives* (Vol. 125, Issue 7, pp. 1–18). https://doi.org/10.1289/EHP1663

Gammon, S., & Jarratt, D. (2019). Keeping leisure in mind. The intervening role of leisure in the blue space - health nexus. In R. Foley, R. Kearns, T. Kistemann, & B. Wheeler (Eds.), *Blue Space, Health and Wellbeing* (pp. 38–51). Routledge, London. https://doi.org/10.4324/9780815359159

Gao, T., Zhang, T., Zhu, L., Gao, Y., & Qiu, L. (2019). Exploring psychophysiological restoration and individual preference in the different environments based on virtual reality. *International Journal of Environmental Research and Public Health*, *16*(17), 1–14. https://doi.org/10.3390/ijerph16173102

Godoy, L. D., Rossignoli, M. T., Delfino-Pereira, P., Garcia-Cairasco, N., & Umeoka, E. H. de L. (2018). A comprehensive overview on stress neurobiology: Basic concepts and clinical implications. *Frontiers in Behavioral Neuroscience*, *12*(July), 1–23.

https://doi.org/10.3389/fnbeh.2018.00127

Gopalan, C., & Kirk, E. (2022). Blood pressure, hypertension, and exercise. In C. Gopalan & E. Kirk (Eds.), *Biology of Cardiovascular and Metabolic Diseases* (pp. 141–156). Elsevier Inc. https://doi.org/10.1016/b978-0-12-823421-1.00007-x

H2020 SOPHIE Consortium. (2020). *A Strategic Research Agenda for Oceans and Human Health in Europe*. H2020 SOPHIE Project. https://doi.org/10.5281/zenodo.3696561

Haluza, D., Schönbauer, R., & Cervinka, R. (2014). Green Perspectives for Public Health: A Narrative Review on the Physiological Effects of Experiencing Outdoor Nature. *International Journal of Environmental Research and Public Health*, *11*(5), 5445–5461. https://doi.org/10.3390/ijerph110505445

Hartig, T. (2011). Issues in Restorative Environments Research: Matters of Measurement. In B. Fernández-Ramírez, C. Hidalgo-Villodres, C. M. Salvador-Ferrer, & M. J. Martos Méndez (Eds.), *Psicología ambiental 2011: Entre los estudios urbanos y el análisis de la sostenibilidad [Environmental psychology 2011: between urban studies and the analysis of sustainability]. (Proceedings of the 11th Biennial Conference on Environmental Psychology).* (pp. 1–20).

Hartig, T., Mitchell, R., de Vries, S., & Frumkin, H. (2014). Nature and Health. *Annual Review of Public Health*, *35*(1), 207–228. https://doi.org/10.1146/annurev-publhealth-032013-182443

Hipp, J. A., & Ogunseitan, O. A. (2011). Effect of environmental conditions on perceived psychological restorativeness of coastal parks. *Journal of Environmental Psychology*, *31*(4), 421–429. https://doi.org/10.1016/j.jenvp.2011.08.008

Hooyberg, A., Michels, N., Allaert, J., Vandegehuchte, M. B., Everaert, G., De Henauw, S., & Roose, H. (2022). 'Blue' coasts: Unravelling the perceived restorativeness of coastal environments and the influence of their components. *Landscape and Urban Planning*, *228*(August), 104551. https://doi.org/10.1016/j.landurbplan.2022.104551

Jensen, C., Vasseljen, O., & Westgaard, R. H. (1993). The influence of electrode position on bipolar surface electromyogram recordings of the upper trapezius muscle. *European Journal of Applied Physiology and Occupational Physiology*, *67*(3), 266–273. https://doi.org/10.1007/BF00864227

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). https://doi.org/10.3390/ijerph16234739

Johal, J., Iwanaga, J., Tubbs, K., Loukas, M., Oskouian, R. J., & Tubbs, R. S. (2019). The Accessory Nerve: A Comprehensive Review of its Anatomy, Development, Variations, Landmarks and Clinical Considerations. *Anatomical Record*, *302*(4), 620–629. https://doi.org/10.1002/ar.23823

Kaplan, R., & Kaplan, S. (1989). *The experience of nature: A psychological perspective*. Cambridge University Press. https://doi.org/10.1037/030621

Katayama, K., & Saito, M. (2019). Muscle sympathetic nerve activity during exercise. *Journal of Physiological Sciences*, *69*(4), 589–598. https://doi.org/10.1007/s12576-019-00669-6

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*(FEB), 1–18. https://doi.org/10.3389/fpsyg.2017.00213

Laine, C. M., Spitler, K. M., Mosher, C. P., & Gothard, K. M. (2009). Behavioral triggers of skin conductance responses and their neural correlates in the primate amygdala. *Journal of Neurophysiology*, *101*(4), 1749–1754. https://doi.org/10.1152/jn.91110.2008

Lange, A. (2001). De DASS: Een vragenlijst voor het meten van depressie, angst en stress.

Gedragstherapie, *34*(1), 35–54.

Largo-Wight, E., O'Hara, B. K., & Chen, W. W. (2016). The Efficacy of a Brief Nature Sound Intervention on Muscle Tension, Pulse Rate, and Self-Reported Stress. *HERD: Health Environments Research & Design Journal*, *10*(1), 45–51. https://doi.org/10.1177/1937586715619741

Litleskare, S., Macintyre, T. E., & Calogiuri, G. (2020). Enable, reconnect and augment: A new era of virtual nature research and application. *International Journal of Environmental Research and Public Health*, *17*(5). https://doi.org/10.3390/ijerph17051738

Malik, M., Bigger, J. T., Camm, A. J., Kleiger, R. E., Malliani, A., Moss, A. J., & Schwartz., P. J. (1996). Heart rate variability: Standards of measurement, physiological interpretation, and clinical use. Task Force of The European Society of Cardiology and The North American Society of Pacing and Electrophysiology. *European Heart Journal*, *17*, 354–381.

Marker, R. J., Campeau, S., & Maluf, K. S. (2017). Psychosocial stress alters the strength of reticulospinal input to the human upper trapezius. *Journal of Neurophysiology*, *117*(1), 457–466. https://doi.org/10.1152/jn.00448.2016

Miyamoto, T., Sotobayashi, D., Ito, G., Kawai, E., Nakahara, H., Ueda, S., Toyama, T., Saku, K., Nakanishi, Y., & Kinoshita, H. (2022). Physiological role of anticipatory cardiorespiratory responses to exercise. *Physiological Reports*, *10*(5). https://doi.org/10.14814/phy2.15210

Osman, A., Wong, J. L., Bagge, C. L., Freedenthal, S., Gutierrez, P. M., & Lozano, G. (2012). The Depression Anxiety Stress Scales-21 (DASS-21): Further Examination of Dimensions, Scale Reliability, and Correlates. *Journal of Clinical Psychology*, *68*(12), 1322–1338. https://doi.org/10.1002/jclp.21908

Paulsen, F., & Waschke, J. (2011). *Sobotta: Atlas of the Human Anatomy - Head, Neck and Neuroanatomy (Vol. 3)* (F. Paulsen & J. Waschke (eds.); 15th editi). Elsevier Urban & Fischer.

Peng, C., Yamashita, K., & Kobayashi, E. (2016a). An Empirical Study on the Effects of the Beach on Mood and Mental Health in Japan. *Journal of Coastal Zone Management*, *18*(4). https://doi.org/10.4172/2473-3350.1000412

Peng, C., Yamashita, K., & Kobayashi, E. (2016b). Effects of the Coastal Environment on Well-being. *Journal of Coastal Zone Management*, *19*(2). https://doi.org/10.4172/2473-3350.1000421

R Core Team. (2018). *R: A language and environment for statistical computing [Computer software]*. R Foundation for Statistical Computing (Vienna, Austria). https://www.r-project.org/

Russo, M. A., Santarelli, D. M., & O'Rourke, D. (2017). The physiological effects of slow breathing in the healthy human. *Breathe*, *13*(4), 298–309. https://doi.org/10.1183/20734735.009817

Severin, M. I., Raes, F., Notebaert, E., Lambrecht, L., Everaert, G., & Buysse, A. (2022). A Qualitative Study on Emotions Experienced at the Coast and Their Influence on Well-Being. *Frontiers in Psychology*, *13*(June). https://doi.org/10.3389/fpsyg.2022.902122

Shaffer, F., & Ginsberg, J. P. (2017). An Overview of Heart Rate Variability Metrics and Norms. *Frontiers in Public Health*, *5*(September), 1–17. https://doi.org/10.3389/fpubh.2017.00258

Shuda, Q., Bougoulias, M. E., & Kass, R. (2020). Effect of nature exposure on perceived and physiologic stress: A systematic review. *Complementary Therapies in Medicine*, *53*(March), 102514. https://doi.org/10.1016/j.ctim.2020.102514

Sjak-Shie, E. E. (2019). *PhysioData Toolbox (Version 0.5.0) [Computer software]*. https://physiodatatoolbox.leidenuniv.nl

Tanja-Dijkstra, K., Pahl, S., White, M. P., Auvray, M., Stone, R. J., Andrade, J., May, J., Mills, I., & Moles, D. R. (2018). The Soothing Sea: A Virtual Coastal Walk Can Reduce Experienced and

Recollected Pain. *Environment and Behavior*, *50*(6), 599–625. https://doi.org/10.1177/0013916517710077

Tipton, M. J., Harper, A., Paton, J. F. R., & Costello, J. T. (2017). The human ventilatory response to stress: rate or depth? *Journal of Physiology*, *595*(17), 5729–5752. https://doi.org/10.1113/JP274596

Triguero-Mas, M., Gidlow, C. J., Martínez, D., De Bont, J., Carrasco-Turigas, G., Martínez-Íñiguez, T., Hurst, G., Masterson, D., Donaire-Gonzalez, D., Seto, E., Jones, M. V., & Nieuwenhuijsen, M. J. (2017). The effect of randomised exposure to different types of natural outdoor environments compared to exposure to an urban environment on people with indications of psychological distress in Catalonia. *PLoS ONE*, *12*(3), 1–17. https://doi.org/10.1371/journal.pone.0172200

Ulrich, R. S., Simons, R. F., Losito, B. D., Fiorito, E., Miles, M. A., & Zelson, M. (1991). Stress recovery during exposure to natural and urban environments. *Environmental Psychology*, *11*, 201–230.

Verster, J. C., Sandalova, E., Garssen, J., & Bruce, G. (2021). The use of single-item ratings versus traditional multiple-item questionnaires to assess mood and health. *European Journal of Investigation in Health, Psychology and Education*, *11*(1), 183–198. https://doi.org/10.3390/ejihpe11010015

Vert, C., Gascon, M., Ranzani, O., Márquez, S., Triguero-Mas, M., Carrasco-Turigas, G., Arjona, L., Koch, S., Llopis, M., Donaire-Gonzalez, D., Elliott, L. R., & Nieuwenhuijsen, M. (2020). Physical and mental health effects of repeated short walks in a blue space environment: A randomised crossover study. *Environmental Research*, *188*(June), 109812. https://doi.org/10.1016/j.envres.2020.109812

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*(6), 1063–1070. https://doi.org/10.1037/0022-3514.54.6.1063

White, M. P., Elliott, L. R., Gascon, M., Roberts, B., & Fleming, L. E. (2020). Blue space, health and well-being: A narrative overview and synthesis of potential benefits. *Environmental Research*, *191*(September), 110169. https://doi.org/10.1016/j.envres.2020.110169

White, M. P., Pahl, S., Ashbullby, K. J., Burton, F., & Depledge, M. H. (2015). The effects of exercising in different natural environments on psycho-physiological outcomes in post-menopausal women: A simulation study. *International Journal of Environmental Research and Public Health*, *12*(9), 11929–11953. https://doi.org/10.3390/ijerph120911929

White, M. P., Smith, A., Humphryes, K., Pahl, S., Snelling, D., & Depledge, M. (2010). Blue space: The importance of water for preference, affect, and restorativeness ratings of natural and built scenes. *Journal of Environmental Psychology*, *30*(4), 482–493. https://doi.org/10.1016/j.jenvp.2010.04.004

White, M. P., Wheeler, B. W., Herbert, S., Alcock, I., & Depledge, M. H. (2014). Coastal proximity and physical activity: Is the coast an under-appreciated public health resource? *Preventive Medicine*, *69*, 135–140. https://doi.org/10.1016/j.ypmed.2014.09.016

White, M. P., Yeo, N., Vassiljev, P., Lundstedt, R., Wallergård, M., Albin, M., & Lõhmus, M. (2018). A prescription for “nature” – the potential of using virtual nature in therapeutics. *Neuropsychiatric Disease and Treatment*, *Volume 14*, 3001–3013. https://doi.org/10.2147/NDT.S179038

Wijsman, J., Grundlehner, B., Penders, J., & Hermens, H. (2013). Trapezius muscle EMG as predictor of mental stress. *ACM Transactions on Embedded Computing Systems*, *12*(4), 1–20. https://doi.org/10.1145/2485984.2485987

Wilder, J. (1958). Modern Psychophysiology and the Law of Initial Value. *American Journal of Psychotherapy*, *12*(2), 199–221. https://doi.org/10.1176/appi.psychotherapy.1958.12.2.199

Wyles, K. J., Pahl, S., Thomas, K., & Thompson, R. C. (2016). Factors That Can Undermine the Psychological Benefits of Coastal Environments: Exploring the Effect of Tidal State, Presence, and Type of Litter. *Environment and Behavior*, *48*(9), 1095–1126. https://doi.org/10.1177/0013916515592177

Yeo, N. L., White, M. P., Alcock, I., Garside, R., Dean, S. G., Smalley, A., & Gatersleben, B. (2020). What is the best way of delivering virtual nature for improving mood?: An experimental comparison of high definition TV, 360º video, and computer generated virtual reality. *Journal of Environmental Psychology*, *141*, 101500. https://doi.org/10.1016/j.jenvp.2020.101500

Zaccaro, A., Piarulli, A., Laurino, M., Garbella, E., Menicucci, D., Neri, B., & Gemignani, A. (2018). How Breath-Control Can Change Your Life: A Systematic Review on Psycho-Physiological Correlates of Slow Breathing. *Frontiers in Human Neuroscience*, *12*(September), 1–16. https://doi.org/10.3389/fnhum.2018.00353

Zipp, P. (1982). Recommendations for the standardization of lead positions in surface electromyography. *European Journal of Applied Physiology and Occupational Physiology*, *50*(1), 41–54. https://doi.org/10.1007/BF00952243