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Does spending time outdoors reduce stress? A review of real-time stress response to outdoor environments

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ABSTRACT

Everyday environmental conditions impact human health. One mechanism underlying this relationship is the experience of stress. Through systematic review of published literature, we explore how stress has been measured in real-time non-laboratory studies of stress responses to deliberate exposure to outdoor environments. The types of exposures evaluated in this review include: nature viewing, outdoor walks, outdoor exercise and gardening. We characterize study design, modalities of stress measurements, and statistical estimates of effect and significance. Heart rate, blood pressure, and self-report measures provide the most convincing evidence that spending time in outdoor environments, particularly those with green space, may reduce the experience of stress, and ultimately improve health. More work is needed to understand effects of in situ modifications to outdoor environments on residents' stress response.

1. Introduction

Stress is the body's physiologic response to real or perceived external threats which can be in reaction to, or modified by, environmental exposures (McEwen and Gianaros, 2010; McEwen and Stellar, 1993). The physiologic changes that accompany stress can be protective, preparing the body to respond to danger or hazards (McEwen, 1998) and can lead to adaption over time (McEwen and Gianaros, 2010). When experienced chronically and in the absence of adequate support and coping mechanisms (McEwen and Gianaros, 2010) however, stress can lead to a wide array of health harms.

Though complex social and economic factors broadly explain the relationship between neighborhood physical environments and health, very limited evaluation of biologic and psychological outcomes has been conducted in real-world settings. It is the goal of this review to assess the extent of research that has explicitly measured physiological and psychological stress response to the physical environments in which people live, work, and play, rather than to laboratory stimuli.

The lack of in situ studies may be due to the complexity of stress as a physiologic state. The stress response is a product of two interrelated biologic systems: the sympathetic-adrenomedullary (SAM) system and the hypothalamic-pituitary-adrenocortical (HPA) system. These systems work together to achieve *allostasis*, or the body's ability to maintain stability through change (Gunnar and Quevedo, 2007; McEwen, 1998). In response to an acute stressor, the SAM system releases hormones like epinephrine and norepinephrine, leading to rapid availability of metabolic resources that increase heart rate, blood flow, as well as amplified vigilance and focused attention. This is the "fight-or-flight" response. The experience of acute stress also activates the HPA system, leading to the release of cortisol, which relates to glycemic and vascular control.

In research, physiologic stress is measured through markers of SAM and HPA system activation. Heart rate, a common marker of the SAM system, changes in response to the neurohormones norepinephrine and epinephrine. Cortisol, a marker of HPA system activation, exhibits a diurnal pattern that includes a steep rise after waking, followed by a drop over the next several hours, and decline until bedtime.

Stress is also commonly represented by an index measure called allostatic load (AL). AL reflects the cumulative, multisystem impact of repeated stress (Juster et al., 2010; Seeman et al., 2010). AL is operationalized by combining markers such as norepinephrine, cortisol, and interleukin-6 with metabolic and cardiovascular outcomes such as blood pressure, heart rate, cholesterol, and glycosylated hemoglobin (Hb_{A1c}), that reflect wear and tear on the body over time (Beckie, 2012). AL may be related to presence or absence of green space or vegetated land cover in the neighborhood environment (Egorov et al., 2017).

Exposure to chronic stress has been associated with alterations in stress markers, and in turn, indicators of poor health. For example,

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stress is associated with deviations from the normal cortisol diurnal pattern (Do et al., 2011; Hajat et al., 2015; Karb et al., 2012; Miller et al., 2007). These deviations occur more prevalently in deprived neighborhoods (Roe et al., 2013), or among populations with low education or minority race/ethnicity status (Karlamangla et al., 2013), and have been linked to negative health outcomes including cardiovascular disease mortality (Kumari et al., 2011), depression and anxiety disorders (Doane et al., 2013), type 2 diabetes (Hackett et al., 2014), memory impairment (Lupien et al., 1998), and immunosuppression (Cacioppo et al., 2002). Similarly, high AL in adolescents is associated with poor mental health, increased incidence of asthma, and poor health outcomes later in life (Bahreinian et al., 2013; Evans et al., 2007; Jackson et al., 2010). Among elderly populations, AL has been associated with cardiovascular disease, physical decline, cognitive function and depression (Juster et al., 2010; Seeman et al., 2001, 1997).

A growing number of studies measure stress and related indicators as a means to understand the relationship between neighborhood environments and human health. This line of inquiry is important, as changes in physiologic stress may be detected prior to the onset of disease. However, only a subset of these studies measure real time stress response (using pre- and post-measurement) to physical environment exposure. The relationship between health outcomes and features of neighborhood environments such as disorder, pedestrian and other transportation infrastructure, or green space, often uses residential location as a proxy for exposure. This does not capture the nuance of exposures that people may experience as they leave their homes and traverse various time-activity zones throughout the day. Using a home address as an estimate of exposure to neighborhood conditions has been shown to bias exposure estimates and calculations of risk (Culyba et al., 2018).

Real-time measurement may also permit evaluation of the nuances in stress responses to environmental stimuli. Some markers of stress exhibit immediate response to external stimuli and there is value in measuring this short-term response as it occurs, as opposed to occasional measurements in laboratory settings. In addition, only a sample of these studies measure stress response to actual physical environments, as opposed to simulated laboratory environments. The purpose of this review is to systematically review characteristics of studies evaluating the stress response to physical, or outdoor, environmental exposures.

2. Methods

We followed Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2009) when conducting and reporting this systematic review. The primary question that we addressed is: How is stress measured in real-time non-laboratory studies of exposures to outdoor environments? To address this question we searched biomedical and social science databases in October 2016, including: Web of Science, PubMed, PsychINFO, Cochrane, and Medline. We did not restrict searches by date of publication and saved all references using Endnote X7 reference manager.

We submitted a standard Boolean search phrase, with syntax tailored to each database. In Web of Science we submitted the following search phrase: (green space*" OR "greenspace" OR "green exercise" OR "green landscape*" OR "natural space" OR "sounds of nature" OR "nature sound*" OR "natural environment*" OR "natural landscape" OR "urban nature" OR "nearby nature" OR "nature view*" OR "tree cover" OR "exposure to nature" OR "outdoor nature" OR "natural space" OR "nature contact" OR "contact with natur*" OR "outdoor environment*" OR greening OR greenness OR neighborhood OR neighborhood* OR park OR "vacant lot*" OR gardening OR "urban environment*" OR "urban forest" OR "urban field settings" OR "viewing nature" OR "forest walking" OR "forest environment*" OR shinrin OR "forest recreation" OR "forest bathing") AND (stress OR "environmental stressor*" OR "blood pressure" OR neuro* OR endocrine OR physiologic* OR psychophysiologic* OR allostatic).

We sought to identify studies that measured biologic indicators linked to the physiologic stress response, as well as self-reported psychological indicators relating to mood, anxiety, distress, perceived stress, restoration, cognitive function, and attention. We considered studies that measured these responses to exposure to any outdoor environments. While most environments involved parks, nature, green space, or forest, we did not select these studies exclusively. We included studies in which stress was the primary outcome of interest. We therefore did not include studies in which stress was measured and used as a mediator (covariate) to another health outcome.

Fig. 1 illustrates our study selection process. The initial searches identified 10,519 references. The three authors used consensus to determine study inclusion criteria and specific inclusion decisions. We first excluded non-human-based studies, and papers not available in English, leaving 3311 studies. We then removed non-original research articles such as reviews, and studies that tested stress response to laboratory stimuli, such as on-screen images, or indoor environments (3080 remained). We excluded 2973 duplicate records. Each author then independently reviewed the remaining papers to determine eligibility. Papers with author disagreement were resolved through discussion and the development of consensus. Based on this review, we

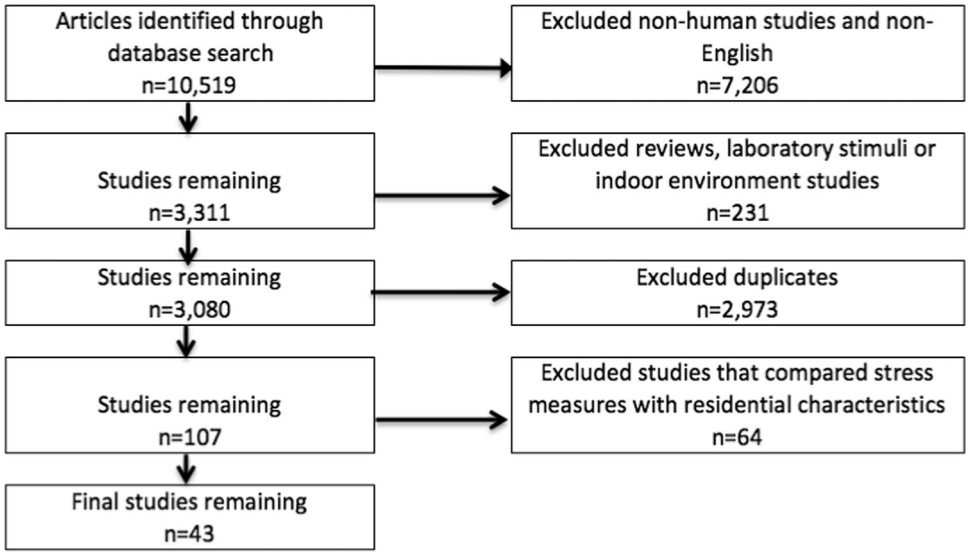

Fig. 1. Selection process for studies of stress response to outdoor environment exposures.

excluded 64 additional studies that calculated environmental exposures using spatial databases given participants' residential addresses rather than measuring explicit and deliberate exposure to outdoor environments.

From each study we recorded research aims, study design, location, years, unit(s) of analysis, sample size, population demographics, environmental exposure, stress outcome(s), measurement procedure and instruments, inclusion of a stress task, and covariates in statistical models. In addition, we recorded effect direction and p-value. Many studies conducted repeated measures of stress indicators in two or more environments (e.g. treatment and control locations). These studies reported statistical differences for stress measures by time, location, and often time × environment. In this case, we report effect direction and p-value for difference comparisons between measurements taken directly before and after experimental (outdoor) exposures, and if available between outdoor environment locations and control locations.

3. Results

Our search identified 43 papers that met our inclusion criteria (Table 1).

3.1. Location and study design

Twenty-three of the 43 studies (Gathright et al., 2006; Horiuchi et al., 2014; Lee et al., 2009, 2011, 2014; Li et al., 2008, 2011; Matsunaga et al., 2011; Morita et al., 2011; Ochiai et al., 2015; Ohtsuka et al., 1998; Park et al., 2008, 2010, 2009; Song et al., 2014, 2015a, 2015b, 2013a, 2013b; Toda et al., 2013; Tsunetsugu et al., 2013, 2007; Yamaguchi et al., 2006) were conducted in Japan, including early studies of physiological response to shinrin-yoku or "forest bathing." Seven of the remaining studies were conducted in the US (Beil and Hanes, 2013; Detweiler et al., 2015; Hartig et al., 2003, 1991; Rodiek, 2002; South et al., 2015; Teas et al., 2007), five in the UK (Aspinall et al., 2015; Gidlow et al., 2016; Gladwell et al., 2016; Hawkins et al., 2011; Roe and Aspinall, 2011), two in South Korea (Joung et al., 2015; Lee, 2010), two in Sweden (Kjellgren and Buhrkall, 2010; Ottosson and Grahn, 2005), and one each in Finland (Tyrväinen et al., 2014), Norway (Calogiuri et al., 2016), Netherlands (van den Berg and Custers, 2011), and Lithuania (Grazuleviciene et al., 2016).

All studies employed experimental study designs comparing pre-post exposure measures (Table 1). Twenty-four studies used a within-subjects design, in which all participants were exposed to each treatment condition or environment (Beil and Hanes, 2013; Gathright et al., 2006; Gidlow et al., 2016; Gladwell et al., 2016; Hartig et al., 2003; Horiuchi et al., 2014; Joung et al., 2015; Lee et al., 2011, 2014; Li et al., 2008, 2011; Matsunaga et al., 2011; Ochiai et al., 2015; Park et al., 2010; Roe and Aspinall, 2011; Song et al., 2014, 2015a, 2015b, 2013a, 2013b; Teas et al., 2007; Toda et al., 2013; Tsunetsugu et al., 2007; Tyrväinen et al., 2014). Eighteen studies used a between-subjects study design in which participants were divided in to groups, for example a treatment and control group, and each group was exposed to different conditions (Aspinall et al., 2015; Calogiuri et al., 2016; Detweiler et al., 2015; Grazuleviciene et al., 2016; Hartig et al., 1991; Hawkins et al., 2011; Kjellgren and Buhrkall, 2010; Lee et al., 2009; Lee, 2010; Morita et al., 2011; Ohtsuka et al., 1998; Ottosson and Grahn, 2005; Park et al., 2008, 2009; Rodiek, 2002; Tsunetsugu et al., 2013; van den Berg and Custers, 2011; Yamaguchi et al., 2006). One study used a comparison group pre-post design (South et al., 2015).

Twenty-four of the 43 studies included a randomized study component in which either the sample (Kjellgren and Buhrkall, 2010; Toda et al., 2013), study group assignment (Calogiuri et al., 2016; Detweiler et al., 2015; Gladwell et al., 2016; Grazuleviciene et al., 2016; Hartig et al., 2003; Kjellgren and Buhrkall, 2010; Lee et al., 2009, 2011, 2014; Ottosson and Grahn, 2005; Park et al., 2008, 2010, 2009; Rodiek, 2002; Song et al., 2015b, 2013a; Tsunetsugu et al., 2007; van den Berg and Custers, 2011), order of treatment site visitation (Beil and Hanes, 2013; Gidlow et al., 2016; Horiuchi et al., 2014; Tyrväinen et al., 2014), or treatment location (South et al., 2015) was randomized.

Most studies collected data at varying times during the experiment. For example, physiological measures were often collected before and after the environment exposure. In some cases measurements were taken during the exposure, and/or after a period following the exposure. Thirteen studies conducted continuous monitoring of physiological indicators such as heart rate, heart rate variability, blood pressure, or emotional experience (Aspinall et al., 2015; Gathright et al., 2006; Horiuchi et al., 2014; Joung et al., 2015; Lee et al., 2014; Park et al., 2008; Song et al., 2014, 2015a, 2015b, 2013b; South et al., 2015; Tsunetsugu et al., 2013, 2007). Ten studies used an accelerometer to record energy expenditure (Lee et al., 2011, 2014; Lee, 2010; Li et al., 2008; Ochiai et al., 2015; Park et al., 2008, 2009; Song et al., 2014, 2015a, 2013b).

3.2. Environmental exposure settings

Studies employed one of four types of environmental exposures: nature viewing, outdoor walk, outdoor exercise or gardening. Table 1 describes experimental exposure and settings. More than half of the studies (n = 25) involved an outdoor walk as the mechanism of environmental exposure (Aspinall et al., 2015; Gidlow et al., 2016; Gladwell et al., 2016; Grazuleviciene et al., 2016; Hartig et al., 2003, 1991; Hawkins et al., 2011; Lee et al., 2014; Li et al., 2011; Morita et al., 2011; Ochiai et al., 2015; Ohtsuka et al., 1998; Park et al., 2010, 2009; Roe and Aspinall, 2011; Song et al., 2014, 2015a, 2015b, 2013b; South et al., 2015; Teas et al., 2007; Toda et al., 2013; Tsunetsugu et al., 2007; Tyrväinen et al., 2014; Yamaguchi et al., 2006). Participants were asked to walk a certain distance or amount of time outside, mostly one time, but in some cases repeated times.

Eleven studies collected measures of stress response to viewing landscapes (Beil and Hanes, 2013; Horiuchi et al., 2014; Joung et al., 2015; Kjellgren and Buhrkall, 2010; Lee et al., 2009, 2011; Li et al., 2008; Matsunaga et al., 2011; Park et al., 2008; Song et al., 2013a; Tsunetsugu et al., 2013). Nature viewing involved passive exposure to environments. Participants may have been asked to sit or lie down and view an outdoor setting in both a built and natural location. The practice of shinrin-yoku involved nature viewing, though often in combination with walking. One study (Park et al., 2009) asked participants to both view landscapes and complete an outdoor walk on the same day.

Two studies tested the effects of outdoor exercise, included biking and strength exercises (Calogiuri et al., 2016) and tree climbing (Gathright et al., 2006) on stress response. The remaining five studies involved some form of outdoor gardening (Detweiler et al., 2015; Lee, 2010; Ottosson and Grahn, 2005; Park et al., 2009; Rodiek, 2002; van den Berg and Custers, 2011).

Seventeen of the studies were conducted in both natural and built environments, with the natural environment serving as the treatment, and built or urban environment serving as the control condition (Gidlow et al., 2016; Gladwell et al., 2016; Grazuleviciene et al., 2016; Hartig et al., 2003, 1991; Joung et al., 2015; Lee et al., 2009, 2011, 2014; Li et al., 2011; Park et al., 2008, 2010, 2009; Roe and Aspinall, 2011; Tsunetsugu et al., 2013; Tyrväinen et al., 2014; Yamaguchi et al., 2006). Twelve studies were conducted solely in forested or rural settings (Gathright et al., 2006; Hawkins et al., 2011; Horiuchi et al., 2014; Li et al., 2008; Morita et al., 2011; Ochiai et al., 2015; Ohtsuka et al., 1998; Song et al., 2015b, 2013a; Toda et al., 2013; Tsunetsugu et al., 2007; van den Berg and Custers, 2011). Thirteen studies were conducted in urban settings, although often in a range of settings from highly built to highly natural park settings (Aspinall et al., 2015; Beil and Hanes, 2013;

Table 1
Characteristics of studies that report stress outcome measurements in response to physical exposures.

Citation	Study design	Country	Sample size	Sample	Mean age	Sex	Environment exposure	Procedure/Timing	Stress outcome	Effect direction	p-value
Aspinall et al. (2015)	Between-subjects	UK	12	University students	31	Both	Outdoor walk	25 min/walking in urban shopping street, green space, commercial district	Emotion	–	NA
Beil and Hanes (2013)	Within-subjects	US	15	Non-Hispanic White	42	Both	Nature viewing	20 min/exposure to 1) very natural, 2) mostly natural, 3) mostly built, & 4) very built urban settings	Alpha amylase	ND	
									Cortisol	ND	
									Perceived stress	–	< 0.01
Calogiuri et al. (2016)	Between-subjects	Norway	14		49	Both	Outdoor exercise	45 min/exercise in outdoor green vs indoor settings	BP	–	< 0.05
									Cortisol (saliva)	–	< 0.05
									Cortisol (blood)	ND	
									mood	+	< 0.01
									Restoration	+	< 0.001
Detweiler et al. (2015)	Between-subjects	US	24	Veterans with substance abuse diagnoses	46	Male*	Outdoor gardening	1 h per day, 5 days per week for 3 weeks/gardening activities	Cortisol	ND	
Gathright et al. (2006)	Within-subjects	Japan	11	University students and faculty members	27	Both	Outdoor exercise	Tower vs tree climbing	Cortisol	–	DNR
									Heart rate	DNR	
									IBI	+	< 0.01
									Mood	- (tension, confusion, fatigue), + (vitality)	< 0.05
Gidlow et al. (2016)	Within-subjects	UK	38	Healthy adults	41	Both	Outdoor walk	30 min/walking in residential (urban) vs natural vs blue (natural with water) settings	Cortisol	ND	
									Heart rate	DNR	
									HF component	ND	
									LF component	ND	
									RR interval	ND	
									SDNN	ND	
									Cognitive function	+	< 0.05
									Mood	ND	
									Restoration	+	< 0.05
Gladwell et al. (2016)	Within-subjects	UK	13	Healthy adults	39	Both	Outdoor walk	Walking in natural vs built settings	BP	DNR	
									Heart rate	ND	
									rMSSD	+	< 0.05
									RR interval	ND	
									SD1	+	< 0.05
									SDNN	+	< 0.05
									Sleep duration	ND	
Grazuleviciene et al. (2016)	Between-subjects	Lithuania	20	Kaunas city residents	62	Male	Outdoor walk	30 min for 7 consecutive days/walking in urban park vs street environment	BP	–	< 0.001
									Cortisol	ND	
									Heart rate	ND	
									Mood	ND	
Hartig et al. (2003)	Within-subjects	US	112	University students	21	Both	Outdoor walk	60 min/sitting indoors vs walking outdoors	Attention	ND	
									BP	ND	
									Mood	+ (happiness, positive emotion), - (anger, aggression)	< 0.01
Hartig et al. (1991)	Between-subjects	US	34	College students	20	Both	Outdoor walk	40 min/walking in nature vs urban built vs passive relaxation	BP	ND	
									Heart rate	ND	
									mood	+ (happiness), - (anger/ aggression)	< 0.01
Hawkins et al. (2011)	Between-subjects	UK	94	Members of local activity groups		Both	Outdoor walk	No longer than 30 min/indoor exercise vs walking vs allotment gardening vs home gardening	BP	–	DNR
									Perceived stress	–	< 0.05

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Table 1 *(continued)*

Citation	Study design	Country	Sample size	Sample	Mean age	Sex	Environment exposure	Procedure/Timing	Stress outcome	Effect direction	p-value
Horiuchi et al. (2014)	Within-subjects	Japan	15	Healthy adults	36	Both	Nature viewing	15 min/viewing forest vs no view	Alpha amylase	ND	
									BP	ND	
									LF component	ND	
									HF component	ND	
									LF/HF component	ND	
									VLF component	ND	
									Mood	- (trait-anxiety, depression, fatigue, confusion)	< 0.05
									Oxygenated hemoglobin	–	< 0.05
Joung et al. (2015)	Within-subjects	South Korea	8	University students	22	ND	Nature viewing	15 min/viewing forest vs viewing built urban	Total hemoglobin	–	< 0.05
									Oxygenated hemoglobin	–	< 0.05
									Mood	+ (comfortable, natural, soothed, vigor), - (anger, fatigue, mood disturbance)	< 0.05
Kjellgren and Buhrkall (2010)	Between-subjects	Sweden	18	Diagnosis of stress and/or burnout syndrome	37	Both	Nature viewing	30 min/relaxation in oudoor setting vs simulated environment	BP	–	< 0.05
									Heart rate	ND	
									Perceived stress	ND	
Lee et al. (2009)	Between-subjects	Japan	12	Healthy adults	21	Male	Nature viewing	30 min/viewing forest vs built urban	BP	–	< 0.05
									Cortisol	–	< 0.01
									Heart rate	–	< 0.05
Lee et al. (2011)	Within-subjects	Japan	12	University students	21	Male	Nature viewing	15 min/viewing forest vs built urban	BP	ND	
									Cortisol	ND	
									Heart rate	–	< 0.01
									LF component	+	< 0.05
									HF component	+	< 0.05
									LF/HF component	+	< 0.05
									IBI	+	< 0.05
									Mood	+ (vigour), - (tension-anxiety, fatigue, confusion, total mood disturbance),	< 0.01
Lee et al. (2014)	Within-subjects	Japan	46	Healthy adults	21	Male	Outdoor walk	12–15 min/walking in forest vs built settings	Anxiety	+	< 0.01
									BP	ND	
									Heart rate	–	< 0.01
									HF component	+	< 0.01
									LF/HF component	–	< 0.01
									Mood	+	< 0.01
Lee (2010)	Between-subjects	South Korea	30	Mentally challenged adults	23	Both	Outdoor gardening	60 min, 7 times/horticultural activities	Cortisol	–	< 0.05
									HF component	ND	
									LF component	ND	
									SDNN	ND	
									TP	ND	
Li et al. (2008)	Within-subjects	Japan	13	Nurses	29	Female	Nature viewing	120 min/walking in forest	Adrenaline	–	< 0.05
									Noraderaline	–	< 0.05
									Estradiol	ND	
									Progesterone	+	< 0.05
									Mood	+ (vigour), - (anxiety, depression, fatigue, confusion)	< 0.05
									NK activity	+	< 0.01

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Table 1 *(continued)*

Citation	Study design	Country	Sample size	Sample	Mean age	Sex	Environment exposure	Procedure/Timing	Stress outcome	Effect direction	p-value
Li et al. (2011)	Within-subjects	Japan	16	Healthy adults	57	Male	Outdoor walk	120 min/walking in forest vs built settings	BP	–	< 0.05
									Blood glucose	ND	
									Total cholesterol	ND	
									Triglycerides	ND	
									Insulin	ND	
									DHEA-S	+	< 0.05
									NT-proBNP	+	< 0.05
									CRP	ND	
									Adrenaline	ND	
									Noraderaline	–	< 0.05
									Dopamine	–	< 0.05
									Hemoglobin	ND	
									Sleep-actigraph	ND	
Matsunaga et al. (2011)	Within-subjects	Japan	30	Seniors needing walking assistance	82	Female	Nature viewing	12 min/walking in rooftop garden vs car park	HF component	+	< 0.01
									LF component	+	< 0.01
									LF/HF component	+	< 0.01
Morita et al. (2011)	Between-subjects	Japan	71	Adults with sleep complaints		Both	Outdoor walk	2 h/walking in forest	Sleep-self report	+	< 0.05
									Sleep-actigraph	+ (sleep time, actual sleep %, immobile sleep time)	< 0.05
Ochiai et al. (2015)	Within-subjects	Japan	17	Healthy adults	62	Female	Outdoor walk	4 h 41 min/walking in forest	BP	DNR	
									Cortisol	–	< 0.05
									Heart rate	–	< 0.01
									Mood	+ (comfortable, relaxed, natural, vigor), - (tension-anxiety)	< 0.01
Ohtsuka et al. (1998)	Between-subjects	Japan	87	Non-insulin-dependent diabetic patients	61	Both	Outdoor walk	30 or 60 min/walking in forest	Blood glucose	–	< 0.0001
									BP	–	< 0.05
									Heart rate	ND	
Ottosson and Grahn (2005)	Between-subjects	Sweden	17	Residents of a geriatric home	86	Both	Outdoor gardening	60 min/gardening vs indoor time	BP	–	< 0.05
									Heart rate	–	< 0.05
Park et al. (2010)	Within-subjects	Japan	280	University students	22	Male	Outdoor walk	30 min/walking and viewing forest vs built urban settings	BP	–	< 0.05
									Heart rate	–	< 0.01
									HF component	+	< 0.01
									LF/HF component	+	< 0.01
									Cortisol	–	< 0.01
									Immunoglobulin A	DNR	
									Mood	- (trait-anxiety, depression, fatigue, confusion), + (vigor)	< 0.05
Park et al. (2008)	Between-subjects	Japan	12	University students	21	Male	Nature viewing	15 min/walking and viewing forest vs built urban settings	BP	ND	
									Heart rate	–	< 0.01
									HF component	+	< 0.05
									LF component	+	< 0.05
									LF/HF component	+	< 0.05
									Cortisol	–	< 0.05
									Mood	+ (comfortable, calm, refreshed)	< 0.05
Park et al. (2009)	Between-subjects	Japan	12	University students	22	Male	Outdoor gardening	15 min/walking and viewing forest vs built urban settings	BP	–	< 0.05
									Heart rate	–	< 0.01
									HF component	+	< 0.05
									LF/HF component	+	< 0.05
									Mood	+ (comfortable, calm, refreshed)	< 0.01

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Table 1 *(continued)*

Citation	Study design	Country	Sample size	Sample	Mean age	Sex	Environment exposure	Procedure/Timing	Stress outcome	Effect direction	p-value
Rodiek (2002)	Between-subjects	US	17	Residents of a residential complex for aging	85	Female	Outdoor gardening	< 150 min/exposure to garden vs indoor setting	Anxiety	ND	
									Cortisol	–	< 0.1
									Mood	ND	
Roe and Aspinall (2011)	Within-subjects	UK	24	healthy adults; adults with poor mental health	41	Both	Outdoor walk	1 h/walking in urban vs rural park settings	Cognitive function	- (challenge)	< 0.05
									Mood	+ (hedonic tone)	< 0.05
									Perceived stress	–	< 0.05
Song et al. (2013a)	Within-subjects	Japan	13	University students	23	Male	Outdoor walk	15 min/walking in urban park	Heart rate	–	< 0.05
									HF component	+	< 0.05
									LF component	ND	< 0.05
									LF/HF component	ND	< 0.05
									Mood	+ (comfortable, natural, relaxed, vigor), - (tension-anxiety)	< 0.01
Song et al. (2014)	Within-subjects	Japan	17	University students	21	Male	Outdoor walk	15 min/walking in urban park vs built urban settings	Heart rate	–	< 0.05
									HF component	+	< 0.01
									LF component	ND	< 0.01
									LF/HF component	ND	< 0.01
									Mood	+ (comfortable, natural, relaxed, vigor), - (tension-anxiety, fatigue)	< 0.05
Song et al. (2015a)	Within-subjects	Japan	23	University students	22	Male	Outdoor walk	15 min/walking in urban park vs built urban settings	Heart rate	–	< 0.01
									HF component	+	< 0.01
									LF component	ND	< 0.01
									LF/HF component	–	< 0.01
									Mood	+ (comfortable, natural, relaxed, vigor), -(tension-anxiety, anger-hostility, fatigue, confusion)	< 0.05
Song et al. (2015b)	Within-subjects	Japan	20	Healthy adults	58	Male	Outdoor walk	17 min/walking in urban park vs built urban settings	Heart rate	–	< 0.05
									HF component	+	< 0.05
									LF component	ND	< 0.05
									LF/HF component	ND	< 0.05
									Mood	+ (comfortable, natural, relaxed, vigor), -(tension-anxiety, anger-hostility, fatigue, confusion)	
Song et al. (2013b)	Within-subjects	Japan	485	University students	22	Male	Nature viewing	15 min/walking in forest vs built urban settings	BP	–	< 0.05
									Heart rate	–	< 0.01
South et al. (2015)	Comparison group pre-post	US	12				Outdoor walk	7–15 min (treatment) 6–10 min (control)/walking in residential area past blighted vs greened vacant lots	Heart rate	–	< 0.001
Teas et al. (2007)	Within-subjects	US	19	Post-menopausal women	58	Female		60 min/walking in outdoor vs indoor settings	Alpha amylase	DNR	
									Cortisol	ND	
									mood	+(pleased, delighted, joy, happy), - (frustration, worry, anger, sad)	< 0.1
Toda et al. (2013)	Within-subjects	Japan	20	Healthy adults	68	Male	Outdoor walk	1000 m walk at own pace/ walking in forest	BP	–	< 0.05
									Cortisol	–	< 0.05
									Heart rate	DNR	
									Chromogranin A	+	< 0.05

(continued on next page)

Table 1 *(continued)*

Citation	Study design	Country	Sample size	Sample	Mean age	Sex	Environment exposure	Procedure/Timing	Stress outcome	Effect direction	p-value
Tsunetsugu et al. (2007)	Within-subjects	Japan	12	University students	22	Male	Outdoor walk	15 min/walking and viewing forest setting	BP	–	< 0.05
									Heart rate	ND	
									HF component	ND	< 0.05
									LF	ND	< 0.05
									LF/HF component	ND	< 0.05
									Cortisol	–	< 0.05
									Immunoglobulin A	ND	
									Mood	+ (comfortable, calm, refreshed)	< 0.05
Tsunetsugu et al. (2013)	Between-subjects	Japan	48	University students	21	Male	Nature viewing	15 min/walking and viewing forest vs built urban settings	BP	–	< 0.1
									HF component	+	< 0.01
									LF/HF component	–	< 0.01
									Mood	+ (comfort, soothing, natural, refreshment), -(tension-anxiety, fatigue, confusing, vigor)	< 0.01
Tyrvainen et al. (2014)	within-subjects	Finland	77	Healthy adults	58	Both	Outdoor walk	15 min (viewing session), 30 min (walk) / exposure to built urban vs urban park vs urban forest	Cortisol	ND	
									Attention	DNR	
									Mood	+	< 0.01
									Restoration	+	< 0.01
van den Berg and Custers (2011)	Between-subjects	Netherlands	30	Residents of an allotment complex	58	Both	Outdoor gardening	30 min/outdoor gardening vs indoor reading	Cortisol	–	< 0.001
									Mood	+	< 0.05
Yamaguchi et al. (2006)	Between-subjects	Japan	15	University students	22	Male	Outdoor walk	20 min/walking and viewing forest setting	Alpha amylase	ND	

Notes:
Stress Outcome Abbreviations: blood pressure (BP); heart rate variability (HRV); low frequency (LF) component, high frequency (HF) component; low frequency/high frequency (LF/HF) ratio; interbeat interval (IBI); RR interval; root mean squared of successive differences (rMSSD); standard deviation of normal-to-normal intervals (SDNN); Poincare plot (SD1); total power (TP); Dehydroepiandrosterone Sulfate (DHEA-S); N-terminal pro b-type natriuretic peptide (NT-proBNP); and C-reactive protein (CRP); Natural killer cell activity (NK activity). Effect Direction Abbreviations: no statistical difference (ND); did not report (DNR); not applicable (NA).

Detweiler et al., 2015; Kjellgren and Buhrkall, 2010; Lee, 2010; Matsunaga et al., 2011; Ottosson and Grahn, 2005; Rodiek, 2002; Song et al., 2014, 2015a, 2013b; South et al., 2015; Teas et al., 2007). Two studies involved an indoor and outdoor component (Calogiuri et al., 2016; Detweiler et al., 2015).

3.3. Exposure procedures and timing

The amount of time that participants were exposed to treatment and/or control environments ranged from 6 min to 4 h 41 min (see Table 1). Most exposures ranged from 12 to 60 min. In some cases these exposures were repeated, for example, for 7 consecutive days (Grazuleviciene et al., 2016), or for 3 weeks (weekdays only) (Detweiler et al., 2015).

3.4. Stress tasks

The purpose of a stress task is to isolate the effect of treatment by inducing stress or mental fatigue to obtain a uniform state between participants before treatment. Four studies induced stress in participants prior to environmental exposures. van den Berg and Custers (2011) asked participants to complete a Stroop task that tests reaction time using word-color recognition. This study collected stress measurements before and after the stress task, and after experimental activity. Hartig et al. (1991) and Hartig et al. (2003) used the Stroop task followed by a binary classification task to induce cognitive fatigue prior to the environmental exposure. In the case of Hartig et al. (2003), only half of treatment and control participants completed the Stroop task prior to environmental exposure. Kjellgren and Buhrkall (2010) measured stress before and after an induced stress task (Syllogism I-II), and after exposure to either natural or simulated natural environments.

3.5. Stress measurements

Our review identified seven modes of stress outcome measurements, including anthropometric measurements of the cardiovascular system (CVS), saliva, blood, urine, actigraph, electroencephalography, and self-report. Each mode of measurement involved one or more stress outcomes, which are defined in Table 2A. The number of times each stress outcome was employed, listed by modality of measurement and classified by physical exposure setting, is shown in Table 2B. We did not conduct a meta-analysis of study findings because of the varied nature of study procedures and reporting of results, and inadequate number of studies for each stress measurement.

3.5.1. Anthropometric

Thirty-one of the 42 studies included anthropometric measurements of the cardiovascular system, including blood pressure (BP), heart rate (HR), and heart rate variability (HRV) (Calogiuri et al., 2016; Gathright et al., 2006; Gidlow et al., 2016; Gladwell et al., 2016; Grazuleviciene et al., 2016; Hartig et al., 2003, 1991; Hawkins et al., 2011; Horiuchi et al., 2014; Kjellgren and Buhrkall, 2010; Lee et al., 2009, 2011, 2014; Lee, 2010; Li et al., 2011; Matsunaga et al., 2011; Ochiai et al., 2015; Ohtsuka et al., 1998; Ottosson and Grahn, 2005; Park et al., 2008, 2010, 2009; Song et al., 2014, 2015a, 2015b, 2013a, 2013b; South et al., 2015; Toda et al., 2013; Tsunetsugu et al., 2013, 2007). Twenty-two studies measured BP (Calogiuri et al., 2016; Gladwell et al., 2016; Grazuleviciene et al., 2016; Hartig et al., 2003, 1991; Hawkins et al., 2011; Horiuchi et al., 2014; Kjellgren and Buhrkall, 2010; Lee et al., 2009, 2011, 2014; Li et al., 2011; Ochiai et al., 2015; Ohtsuka et al., 1998; Ottosson and Grahn, 2005; Park et al., 2008, 2010, 2009; Song et al., 2013a; Toda et al., 2013; Tsunetsugu et al., 2013, 2007). Most measured resting BP, however three studies measured BP continuously using ambulatory monitors, shown in Table 3.

Table 2A
Definitions of stress outcomes by modality of measurement.

Stress outcome	Definition
Anthropometric measurement of CVS	
Blood pressure	Amount of pressure in arteries during contraction (systolic) and relaxation (diastolic) of the heart
Heart rate	Number of times the heart beats per minute
Heart rate variability	Beat-to-beat interval variability of heart rate
Saliva	
Cortisol	Steroid hormone made in the adrenal gland
Alpha amylase	Enzyme playing a role in digestion
Immunoglobulin A	Antibody that plays a role in mucosal immunity
Chromogranin A	Secretory protein found in neuroendocrine tissue
Blood	
Cortisol	See above
Blood glucose	Simple sugar used by the body as energy source
Oxygenated hemoglobin	Hemoglobin that is oxygen bound
Glycated hemoglobin A1c	Hemoglobin that is bound with glucose
Hemoglobin	Red blood cells
Cholesterol	Lipid molecule
Triglycerides	Ester molecule, main component of human body fat
Insulin	Protein hormone involved in nutrient metabolism
DHEA-S	Steroid hormone produced in adrenal gland
NT-proBNP	Prohormone
CRP	Acute phase protein produced in liver
NK activity	Cytotoxic lymphocyte cell
Progesterone	Steroid hormone
Estradiol	Steroid hormone
Urine	
Adrenaline	Hormone secreted by adrenal gland
Noraderaline	Hormone secreted by adrenal gland
Dopamine	Neurotransmitter
Actigraph	
Sleep	Sleep time, sleep efficiency, immobile minutes, and sleep latency
Self-report	
Mood	Various measures used
Attention	Unified system for control of mental processing
Restoration	Recovery from attention fatigue
Perceived stress	Feelings of psychological pain, strain or pressure
Sleep	sleep depth, number of awakenings, sleep quality, alertness on waking, and difficulty falling asleep
Electroencephalography	
Emotions	Various measures used

Definition sources:
Kaplan, S,1995. The restorative benefits of nature: Toward an integrative framework. *J. Env. Psychol*, 15(3), 169–182.
Lazarus, RS, 1966. Psychological stress and the coping process. New York, NY, US: McGraw-Hill.
Posner, MI, Petersen, SE, 1990. The attention system of the human brain. *Ann. Rev. Neurosci.* 13(1), 25–42.
Salimetrics, Salimetrics.com, accessed 20 February 2018.

Twenty-three studies monitored HR (Gathright et al., 2006; Gidlow et al., 2016; Gladwell et al., 2016; Grazuleviciene et al., 2016; Hartig et al., 1991; Kjellgren and Buhrkall, 2010; Lee et al., 2009, 2011, 2014; Ochiai et al., 2015; Ohtsuka et al., 1998; Ottosson and Grahn, 2005; Park et al., 2008, 2010, 2009; Song et al., 2014, 2015a, 2015b, 2013a, 2013b; South et al., 2015; Toda et al., 2013; Tsunetsugu et al., 2013). Thirteen of these studies took stationary measurement of HR while participants were seated or resting, before and after exposure (Grazuleviciene et al., 2016; Hartig et al., 1991; Kjellgren and Buhrkall, 2010; Lee et al., 2009; Ochiai et al., 2015; Ohtsuka et al., 1998; Ottosson and Grahn, 2005; Park et al., 2008, 2010, 2009; Song et al., 2013a; Toda et al., 2013; Tsunetsugu et al., 2007). The remaining nine studies measured ambulatory HR using the technologies de-

Table 2B
Frequency of stress outcome measurements by modality of measurement and outdoor environment exposure category.

	Outdoor exposure category				
Stress outcome	Outdoor walk	Nature viewing	Outdoor exercise	Outdoor gardening	*Total*
Anthropometric measurement of CVS					
BP	13	7	1	1	*22*
Heart rate	16	5	1	1	*23*
HRV-related	10	5	1	1	*17*
Saliva					
Cortisol	8	4	2	4	*18*
Alpha amylase	2	2			*4*
Immunoglobulin A	2				*2*
Chromogranin A	1				*1*
Blood					
Cortisol			1		*1*
Blood glucose	2				*2*
Oxygenated hemoglobin		2			*2*
Glycated hemoglobin A1c	1				*1*
Total hemoglobin		1			*1*
Total cholesterol	1				*1*
Triglycerides	1				*1*
Insulin	1				*1*
DHEA-S	1				*1*
NT-proBNP	1				*1*
CRP	1				*1*
NK activity		1			*1*
Progesterone		1			*1*
Estradiol		1			*1*
Urine					
Adrenaline	1	1			*2*
Noraderaline	1	1			*2*
Dopamine	1				*1*
Actigraph					
Sleep	2				*2*
Self-report					
Mood	16	6	2	2	*26*
Attention	2				*2*
Perceived stress	1	2			*3*
Restoration	2		1		*3*
Sleep	1				*1*
Electroencephalography					
Emotions	1				*1*

Stress Outcome Abbreviations: CVS (cardiovascular system); blood pressure (BP); heart rate variability (HRV); Dehydroepiandrosterone Sulfate (DHEA-S); N-terminal pro b-type natriuretic peptide (NT-proBNP); and C-reactive protein (CRP); Natural killer cell activity (NK activity); electroencephalography (EEG).

scribed in Table 3 (Gathright et al., 2006; Gidlow et al., 2016; Gladwell et al., 2016; Lee et al., 2011; Song et al., 2014, 2015a, 2015b, 2013b; South et al., 2015).

Seventeen studies measured HRV (Gathright et al., 2006; Gidlow et al., 2016; Gladwell et al., 2016; Horiuchi et al., 2014; Lee et al., 2011, 2014; Lee, 2010; Matsunaga et al., 2011; Park et al., 2008, 2010, 2009; Song et al., 2014, 2015a, 2015b, 2013b; Tsunetsugu et al., 2013, 2007). HRV was measured for its low frequency (LF) component, high frequency (HF) component, low frequency/high frequency (LF/HF) ratio, interbeat interval (IBI), RR interval, root mean squared of successive differences (rMSSD), standard deviation of normal-to-normal intervals (SDNN), Poincare plot (SD1), and total power (TP). Thirteen studies monitored HRV continuously during exposure (Gathright et al., 2006; Gidlow et al., 2016; Gladwell et al., 2016; Lee et al., 2011, 2014; Park et al., 2008, 2010, 2009; Song et al., 2014, 2015a, 2015b, 2013b; Tsunetsugu et al., 2007). Table 3 shows that nearly all of these studies used portable ECG monitors.

Fourteen studies found that BP was significantly lower in "green" environments compared to control environments (Calogiuri et al., 2016; Grazuleviciene et al., 2016; Hawkins et al., 2011; Kjellgren and Buhrkall, 2010; Lee et al., 2009, 2011; Ohtsuka et al., 1998; Ottosson and Grahn, 2005; Park et al., 2010, 2009; Song et al., 2013a; Toda et al., 2013; Tsunetsugu et al., 2013, 2007). Six studies found no statistical difference (Hartig et al., 2003, 1991; Horiuchi et al., 2014; Lee et al., 2011, 2014; Park et al., 2008), and two studies did not report differences (Gladwell et al., 2016; Ochiai et al., 2015). Results from comparisons of HR were mixed. Fourteen of the 23 studies that measured HR found that it was significantly lower in green environments compared to in control environments using pre-post comparisons (Lee et al., 2009, 2011, 2014; Ochiai et al., 2015; Ohtsuka et al., 1998; Ottosson and Grahn, 2005; Park et al., 2008, 2010, 2009; Song et al., 2014, 2015a, 2015b, 2013b; South et al., 2015). The remaining studies found no difference (Gladwell et al., 2016; Grazuleviciene et al., 2016; Hartig et al., 1991; Kjellgren and Buhrkall, 2010; Ohtsuka et al., 1998; Tsunetsugu et al., 2007), or no comparison was made.

Three of the 17 studies that measured HRV found no statistical difference in any HRV indicators (Gidlow et al., 2016; Horiuchi et al., 2014; Tsunetsugu et al., 2007). Significant findings of HF component were in a positive direction (Lee et al., 2011, 2014; Lee, 2010; Matsunaga et al., 2011; Park et al., 2008, 2010, 2009; Song et al.,

Table 3
Blood pressure, heart rate and heart rate variability measurement methods.

Measurement Method	No.
Blood Pressure	
Stationary measurement	19
Omron MXR3 BP monitor	1
Accutracker II ambulatory BP/ECG monitor	1
Check-My-Heart handheld HRV device	1
Heart Rate	
Stationary measurement	13
Activtracer HRV & HR monitor	4
Polar wearable HR and IBI monitor	2
eMotion HRV & ecg sensor	1
Garmin Forerunner 205	1
myBeat wearable ecg sensing system	1
Unnamed ambulatory HR monitor	1
Heart Rate Variability	
Stationary measurement	3
Activtracer portable ECG	6
Unnamed portable ECG monitor	3
eMotion sensor	2
myBeat wearable ecg sensing system	1
Polar wearable IBI sensor	1

2014, 2015a, 2015b, 2013b; Tsunetsugu et al., 2013, 2007). Only three of 11 studies that measured LF component found significant (positive) differences (Lee et al., 2011; Matsunaga et al., 2011; Park et al., 2008). Out of the 13 studies that measured LF/HF component, five studies found no difference (Horiuchi et al., 2014; Song et al., 2014, 2015b, 2013b; Tsunetsugu et al., 2007), three found significant negative difference (Lee et al., 2014; Song et al., 2015b; Tsunetsugu et al., 2013) and five found significant positive difference (Lee et al., 2011; Matsunaga et al., 2011; Park et al., 2008, 2010, 2009).

Studies measuring HRV found no difference in RR interval (Gidlow et al., 2016; Gladwell et al., 2016), two studies found no difference in SDNN (Gidlow et al., 2016; Lee, 2010) and one found significant positive difference (Gladwell et al., 2016). Only one study (Gladwell et al., 2016) used Poincare plot and found significant positive difference. Lee (2010) measured Total Power and found no difference. Two studies (Gathright et al., 2006; Lee et al., 2011) measured IBI and both found significant positive difference.

3.5.2. Saliva

Twenty-five studies used saliva as a measurement modality. Eighteen studies measured cortisol concentrations in saliva (Beil and Hanes, 2013; Calogiuri et al., 2016; Detweiler et al., 2015; Gathright et al., 2006; Gidlow et al., 2016; Grazuleviciene et al., 2016; Lee et al., 2009, 2011; Lee, 2010; Ochiai et al., 2015; Park et al., 2008, 2010; Rodiek, 2002; Teas et al., 2007; Toda et al., 2013; Tsunetsugu et al., 2007; Tyrväinen et al., 2014; van den Berg and Custers, 2011). None of the studies measured diurnal cortisol concentration. In general, cortisol saliva samples were taken before and after outdoor exposures, though some studies also collected samples during the exposure (Gathright et al., 2006; van den Berg and Custers, 2011). Saliva samples were either collected using laboratory-provided swabs or storage tubes, and sent to laboratories for analysis.

Seven of the 18 studies found no significant difference between pre and post measurements (Beil and Hanes, 2013; Detweiler et al., 2015; Gidlow et al., 2016; Grazuleviciene et al., 2016; Lee et al., 2011; Teas et al., 2007; Tyrväinen et al., 2014). Eleven of the remaining 13 studies found a statistically significant decrease in cortisol concentrations (Calogiuri et al., 2016; Lee et al., 2009; Lee, 2010; Ochiai et al., 2015; Park et al., 2008, 2010; Rodiek, 2002; Teas et al., 2007; Tsunetsugu et al., 2007; van den Berg and Custers, 2011). Kjellgren and Buhrkall (2010) compared cortisol concentrations before stress task, after stress task and after treatment exposures, and found a significant decrease between post-stress task and post-treatment concentrations.

Seven studies measured stress response other than cortisol using saliva. Four studies measured alpha amylase (Beil and Hanes, 2013; Horiuchi et al., 2014; Teas et al., 2007; Yamaguchi et al., 2006). None of the studies found significant differences. Two studies measured immunoglobulin A (Park et al., 2010; Tsunetsugu et al., 2007). One of these studies (Park et al., 2010) did not report results and the other (Tsunetsugu et al., 2007) found no statistical difference. Toda et al. (2013) measured chromogranin A and found a significant increase.

3.5.3. Blood

Six studies measured stress response using blood markers (Calogiuri et al., 2016; Horiuchi et al., 2014; Joung et al., 2015; Li et al., 2008, 2011; Ohtsuka et al., 1998). All but two studies took pre-post measurements; Horiuchi et al. (2014) took a single measurement, and Joung et al. (2015) took continuous measurements.

Joung et al. (2015) was the only study to use a non-invasive technology to take blood measurements, involving continuous measurement of total hemoglobin during exposure using a NIRS (near-infrared spectroscopy) tissue oxygenation monitor (PocketNIRS Duo). They found significant negative effect on total Hb.

All others assessed the impact of exposures using a single or series of blood samples. A single study (Calogiuri et al., 2016) measured cortisol concentrations in serum. This study found no significant differences when comparing concentrations after exercise sessions in outdoor and indoor environments.

Li et al. (2011) measured blood glucose following walking in a forest versus built urban area and found no difference. Another study (Ohtsuka et al., 1998) compared pre-post exposure (to forest walking) measures of blood glucose and found a significant negative difference.

Three studies compared various measures of hemoglobin in blood samples. Two studies measured oxygenated hemoglobin from blood samples (Horiuchi et al., 2014; Joung et al., 2015). Horiuchi et al. (2014) measured oxygenated hemoglobin following viewing the forest and viewing a sheet and found a significant negative association. Joung et al. (2015) also found a significant negative difference between oxygenated hemoglobin concentrations after viewing natural compared to urban areas. Another study (Ohtsuka et al., 1998) found a significant negative difference between pre-post measurements of glycated hemoglobin A1c in a sub-sample of participants, with at least one month between samples.

In addition to glucose, Li et al. (2011) measured total cholesterol, triglycerides, insulin, Dehydroepiandrosterone Sulfate (DHEA-S), N-terminal pro b-type natriuretic peptide (NT-proBNP), and C-reactive protein (CRP) and found no difference in these measures, with the exception of significant increase in DHEA-S. An earlier study (Li et al., 2008) measured change in NK activity, progesterone and estradiol, and found significant positive difference in NK activity and progesterone and no difference in estradiol.

3.5.4. Urine

Two studies (Li et al., 2008, 2011) measured stress markers in urine, including adrenaline, noradrenaline, and dopamine. One found a significant decrease in adrenaline and noradrenaline (Li et al., 2008). The other found no difference in adrenaline and significant decreases in noradrenaline and dopamine (Li et al., 2011).

3.5.5. Actigraph

Two studies measured sleep quality and quantity using actigraph. Li et al. (2011) monitored participants' sleep duration before and after experimental exposure using an Actiwatch (R) piezo-electric accelerometer. This study found no significant differences in sleep duration in response to forest or urban/built exposures.

One study (Morita et al., 2011) assessed sleep depth, number of awakenings, sleep quality, alertness on waking, and difficulty falling

Table 4
Self-Report Scales.

Stress Outcome	Scale	No.
Anxiety		
	Hospital anxiety depression scale (HAD)	1
	Spielberger State-Trait Anxiety Inventory (STAI)	1
Attention		
	Focus of Attention Scale (TFOAS)	1
	Necker Cube Pattern Control task (NCPCT)	1
Cognitive function		
	Backward Digit Span (BDS)	1
Mood		
	Inventory of Personal Reactions (ZIPERS)	2
	Overall Happiness Scale	2
	Philadelphia Geriatric Center Positive and Negative Affect Rating Scale	1
	Physical Activity Affective Scale (PAAS)	1
	Positive Affect Scale (PAS) and Negative Affect Scale (NAS)	1
	Positive and Negative Affect Scale (PANAS)	3
	Profile of Mood States	14
	Semantic Differential (SD)	5
	Spielberger State-Trait Anxiety Inventory (STAI)	3
	Stress-Refresh feeling test	1
	Unnamed questionnaire	2
	University of Wales Institute of Science and Technology (UWIST) Mood Adjective Checklist (MACL)	1
Perceived stress		
	Unnamed questionnaire	2
	University of Wales Institute of Science and Technology (UWIST) Mood Adjective Checklist (MACL)	1
	Visual Analog Scale (VAS)	1
Restoration		
	Perceived Restorativeness Scale (PRS)	2
	Restoration Outcome Scale	2
Sleep		
	St Mary's Hospital Sleep Questionnaire (SMHSQ)	1

asleep the night before and the night after experimental exposure using a questionnaire. In addition, for a subset of participants, this study assessed actual sleep time, sleep efficiency, immobile minutes, and sleep latency three days prior and two days following experimental exposure using a wrist actigraph (Actiwatch-64). This study found significant improvements after forest exposures to actual sleep time, time of immobile sleep, sleep depth, and sleep quality.

3.5.6. Self-report

There were 30 studies of self-report of affective states or cognitive function relating to changes in stress from environment exposures.

Table 4 shows the self-report scales used in the selected studies, and number of times each scale was used. Mood was assessed in 25 studies primarily using two instruments, the Positive and Negative Affect Schedule (PANAS) (Watson et al., 1988), or the Personal Mood State Tests (POMS) (McNair et al., 1992). Eleven studies used the POMS survey (Gathright et al., 2006; Gidlow et al., 2016; Horiuchi et al., 2014; Joung et al., 2015; Li et al., 2008; Ochiai et al., 2015; Song et al., 2014, 2015a, 2015b, 2013b; Tsunetsugu et al., 2013). POMS poses 65 questions that identify six mood-states (vitality, depression, tension–anxiety, anger–hate, fatigue, and confusion) also using a 5-point scale (definitely negative to definitely positive). Three studies (Grazuleviciene et al., 2016; Tyrväinen et al., 2014; van den Berg and Custers, 2011) used the PANAS, which asks participants to rate their current feelings using 10 positive and 10 negative mood words, using a 5-point scale (1 = Very slightly or not at all, 2 = A little, 3 = Moderately, 4 = Quite a bit, 5 = Extremely). Average scores are used to represent positive or negative mood.

Other measures used included the Inventory of Personal Reactions (ZIPERS) to record positive affect, attentiveness, anger/aggression, fear arousal, and sadness. Two studies (Hartig et al., 2003, 1991) used ZIPERS in combination with the Overall Happiness Scale in both studies. In addition, Lee et al. (2014) used the Emotional State Test, Rodiek (2002) used the Philadelphia Geriatric Center Positive and Negative Affect Rating Scale, and Teas et al. (2007) used the Positive Affect Scale in combination with the Negative Affect Scale. Two studies used an unnamed 13-point scale to measure subjective "comfortable-uncomfortable" and "calm-roused" feelings (Park et al., 2010; Tsunetsugu et al., 2007). Roe and Aspinall (2011) used the University of Wales Institute of Science and Technology (UWIST) Mood Adjective Checklist (MACL) to assess mood (including perceived stress).

In general, studies found statistically significant positive effects on positive emotions and negative effects on negative emotions, though measures varied and results were not entirely consistent.

Other common affective states measured were anxiety, attention, restoration, perceived stress, and sleep quality. Two studies measured anxiety using instruments independent from POMS or PANAS, including the Hospital Anxiety Depress Scale (Lee et al., 2014), and the Spielberger State-Trait Anxiety Inventory (Rodiek, 2002). Lee et al. (2014) found a significant negative effect of outdoor exposure on anxiety while Rodiek (2002) found no effect. Four studies measured perceived stress, each using different measures including a one-item, 0–10 rating scale (Beil and Hanes, 2013), the Perceived Stress Scale (Hawkins et al., 2011), University of Wales Institute of Science and Technology (UWIST) Mood Adjective Checklist (MACL) (Roe and Aspinall, 2011) and the Stress-VAS Scale in combination with a "SE – stress and energy" scale (Kjellgren and Buhrkall, 2010). Three of these studies found a significant negative effect of outdoor exposure on perceived stress, while one study (Kjellgren and Buhrkall, 2010) found no effect.

Two studies used the Perceived Restorativeness Scale (Calogiuri et al., 2016; Tyrväinen et al., 2014), two studies used the Restoration Outcome Scale (Gidlow et al., 2016; Tyrväinen et al., 2014), while another study (Hartig et al., 1991) used an instrument developed by Kaplan and Talbot (1983) to measure restoration in response to outdoor exposures. All reported significant positive influence of outdoor exposures on restoration. In addition, Morita et al. (2011) measured sleep quality before and after forest walking using a self-report survey instrument and found a significant positive (improved) difference.

In general, improvement in self-report stress measures were paired with mixed results (including increase, decrease or no difference detected) of physiological stress measurements. With exception, Calogiuri et al. (2016) found improvements in mood and restoration along with improvements in blood pressure and cortisol measurements; Hawkins et al. (2011) found decrease in both perceived stress and blood pressure; Joung et al. (2015) found that an improvement in mood was accompanied by a decrease in total and oxygenated hemoglobin; and Ochiai et al. (2015) found that improvement in mood was paired with decrease in heart rate and cortisol concentration.

3.5.7. Electroencephalography

Aspinall et al. (2015) was the only study to use mobile electroencephalography (EEG) to monitor emotional experience while participants experienced the study (walking). Whilst participants walked through different urban environmental settings, they wore an Emotiv EPOC wireless EEG headset, and accompanying software translated EEG signals in to four emotional states. Positive emotions were indicators of stress recovery. The study found that participants had higher meditation levels when walking in an urban park – indicative of possible stress recovery

4. Discussion

Our systematic review found 43 studies of physiological and psychological stress response to exposure to outdoor environments. Nearly half of the studies were conducted in Japan, and the rest were conducted in Europe and the US. All studies employed an experimental research design and approximately half included a randomized study design component, however sample sizes for more than half of the studies were small (< 20).

A variety of methods were used to evaluate stress, the most common being anthropometric measurements of the CVS and self-report. Only a few studies used blood, actigraph and EEG as modalities of stress outcome measurement. These studies had small sample sizes, and generated mixed results from which no generalizations can be made.

Studies that used HR, BP and self-report provide the most convincing support for the hypothesis that spending time in outdoor environments reduces the experience of stress and improves health. However, within each of these measurement strategies, there were substantial variations in findings. For example, some studies of HR demonstrated that "green" environmental exposures are associated with HR reduction. Very few studies of HRV, however, garnered similarly significant relationships between lower HRV and outdoor exposures. As biomarkers, coarser and more sensitive measurements like HR can have multiple contributory factors. On the other hand, there is a body of evidence to support the relative specificity of HRV as a metric for both exposure to a stressor and the integrated appraisal of that stressor in light of previous exposures (Thayer et al., 2012). Cortisol is another example of a biomarker that demonstrates mixed effects, the interpretation of which is complicated by known individual variations and lack of evidence for the specificity of cortisol levels as measurement of stress to a targeted exposure. While the majority of studies using salivary cortisol measurements showed significant findings, these results must be interpreted with caution given the lack of reported relationship to the diurnal pattern of cortisol levels within the body.

The hypothesis behind many studies that evaluate the relationship between stress and physical environments is that exposure to the outdoors, particularly green or natural spaces, can lead to stress reduction. This, in turn, is hypothesized to carry long-term health benefits. There are several mechanisms through which this hypothesis may bear out. For example, exposure to green space has been associated with attention restoration and cognitive function (Berman et al., 2008; Kuo, 2001), which may reduce stress. Additionally, spending time outside may increase social contact, both planned and unexpected (Maas et al., 2009), which may reduce stress. Finally, people are often physically active while being outside (Lee and Maheswaran, 2011), which may reduce stress and improve health.

It should be noted that all the studies in this review primarily measured markers of acute stress, or immediate physiologic changes that occurred in response to exposure to the outdoor environment. None of the studies attempted to measure the diurnal pattern of cortisol or AL, which are generally accepted to be makers of chronic stress. AL is comprised of markers from multiple physiologic systems and many of the studies in this review measured more than one of these AL markers. It could be that the requirements of measurement do not lend well to ambulatory monitoring and in situ measurement of stress response. It is also likely that measurements of chronic stress will not change based on one short-term exposure to the outdoor environment.

Only about half of the studies we reviewed included any randomization component. Bias could occur due to non-random sampling, assignment to study groups, order of experimental exposure, or treatment location. In addition, not all studies collected baseline measurements prior to environmental exposure, and in this case no estimate of change in stress induced by the environmental exposure can be gained. Improvements in study design, such as inclusion of pre-post and treatment-control components, sampling of participants from a variety of socio-demographic backgrounds, and randomization, are required to improve generalizability of results.

While we did not exclusively seek studies testing stress response to natural environments, most studies in this review measured the effects of nature exposure on stress response in general, rather than on the effects of routine, residential, environments on stress. Less than a quarter of the studies were conducted solely in urban settings. While some of these studies tested stress response to built settings, with one exception the built location was a commercial or transportation setting. Only one study (South et al., 2015) assessed stress response of participants in their own residential neighborhood with a population known to suffer health inequalities. Low-resource neighborhood environments could pose risk to health. In addition, it should be noted that these studies were conducted primarily in the global North, and studies conducted in a wider range of settings and locations is warranted.

There are many challenges to use of human health sensors necessary to monitor real-time stress responses in non-laboratory environments. This technology is relatively new and has yet to be extensively and rigorously tested to establish its accuracy and reliability for health research. These sensors typically produce frequent measurements (e.g. every minute) that generate a large amount of data that is very time consuming to manage and analyze. It may be challenging for participants to follow a research protocol that involves wearing a conspicuous device, ensure the functionality of the device, and/or incorporate activities or behaviors that require time and effort beyond regular daily tasks. This could explain, in part, the typically small sample sizes in the studies that used these devices to capture stress responses. This could limit the feasibility of running larger experiments, such as randomized controlled trials, that would be necessary to establish causal mechanisms between outdoor exposure, stress, and health.

Exposure to stress has been proposed as one of the ways that environmental and neighborhood conditions "get under the skin" and lead to poor health and associated health disparities (Baum et al., 1999; Brenner et al., 2013; Brunner, 1997; Cohen et al., 2007; Diez Roux and Mair, 2010; Dowd et al., 2009; Evans and Kim, 2013; Hill et al., 2005; Kristenson et al., 2004; Seeman et al., 2010). Conditions such as blight, segregation, poor social cohesion, and violence combine with personal experiences like job insecurity and discrimination to produce a range of persistent stressors (Bird et al., 2010; Merkin et al., 2009; Schulz et al., 2012). These cumulative stressors may lead to permanent biologic changes and the development of illnesses like cardiovascular disease and diabetes (McEwen and Stellar, 1993; Saban et al., 2014; Seeman et al., 1997).

Research that increases our understanding of *every day* exposure to stress and stressors could lead to interventions that reduce health disparities (Dowd et al., 2009). A more nuanced and dynamic understanding of ways that low-resource neighborhood environments affect acute and chronic stress is needed. The studies reviewed have taken a closer step toward measuring ways that micro-environments relate to human health, which will improve our ability to identify the nuanced, and perhaps, dose-response relationship between environmental exposures and stress (Shanahan et al., 2015). Further development of methodological approaches, for example use of time-activity monitoring across space and time, could help characterize the complex matrix of social and physical circumstances, both indoors and outdoors, that contribute to or mitigate stress. Additionally, given the potential benefits of exposure to natural spaces on stress, interventions paired with research are needed most in those neighborhoods that lack close proximity to such spaces.

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