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The autonomic nervous system in its natural environment: Immersion in nature is associated with changes in heart rate and heart rate variability

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Abstract

Stress Recovery Theory (SRT) suggests that time spent in nature reduces stress. While many studies have examined changes in stress physiology after exposure to nature imagery, nature virtual reality, or nature walks, this study is the first to examine changes in heart rate (HR) and vagally mediated HR variability, as assessed by Respiratory Sinus Arrythmia (RSA), after a longer duration of nature exposure. Consistent with SRT, we hypothesized that immersion in nature would promote stress recovery, as indexed by an increase in RSA and a decrease in HR. We also predicted that exposure to nature would improve self-reported mood. We used a within-subjects design ($N = 67$) to assess changes in peripheral physiology before, during, and after a 5-day nature trip. Results demonstrated a significant decrease in RSA and a significant increase in HR during the trip compared to before or after the trip, suggesting that immersion in nature is associated with a shift toward parasympathetic withdrawal and possible sympathetic activation. These results were contrary to our hypotheses and may suggest increased attentional intake or presence of emotions associated with an increase in sympathetic activation. We also found an improvement in self-reported measures of mood during the trip compared to before or after the trip, confirming our hypotheses and replicating previous research. Implications of this study are discussed in the context of SRT.

KEYWORDS

ECG, emotion, environmental psychology, heart rate, HRV, nature, stress

1 | INTRODUCTION

In our modern (Western) world, people are increasingly spending less time outside (Klepeis et al., 2001). Sedentary indoor lifestyles can increase risk for negative health outcomes such as heart disease and obesity (Lichtenstein et al., 2006). Likewise, living in urban areas has been associated with increased levels of stress (Lederbogen et al., 2011). Stress Recovery Theory (SRT; Ulrich et al., 1991) suggests that time spent in natural environments can promote the recovery of stress. Natural environments are broadly defined as "areas that contain elements of living systems that include plants and nonhuman animals across a range of scales and degrees of human management" (Bratman et al., 2012; see, also Wilson, 1984). SRT draws on psycho-evolutionary theory (Plutchik, 1984) to explain how nonthreatening nature reduces stress. This theory suggests that changes in emotional tone and arousal served adaptive purposes to enhance our survival and reproductive success. Such changes would occur quickly and prepare us for fight-or-flight responses to threatening stimuli, such as a rattlesnake encounter. In this example, autonomic activation of stress is adaptive and beneficial to our survival.

Our current environments, however, can promote chronic stress in response to psychological stressors that do not quickly pass (Segerstrom & Miller, 2004). Activating the stress response system frequently and over a longer duration can have deleterious effects on immune functioning and cardiovascular health (Cacioppo et al., 1998; Hawkley & Cacioppo, 2004; Uchino et al., 2007; Ulrich-Lai & Herman, 2009). Although our physiological stress response was adaptive from an evolutionary standpoint in response to a physical threat, our physiological response to modern day stress continues to reflect the demands of earlier environments (Cacioppo et al., 1998). In other words, events or stimuli that do not require a physical response are evoking a physical reaction and causing us to stay in elevated states for longer, threatening our homeostasis (Hobfoll, 1989; Uchino et al., 2007).

1.1 | Stress recovery theory

If humans are readily equipped to respond to threatening stimuli in natural settings (e.g., snakes), Ulrich et al. (1991) argues that humans also have a readiness to quickly acquire restorative responses (e.g., recharge of physical energy) that, by the same logic, may strongly apply in natural settings. Therefore, Ulrich proposes that recovery from stress, a restorative response, will occur more quickly and completely in natural versus urban settings. Ulrich et al. (1991) suggests two main components through which this recovery quickly occurs: (1) activation of the Parasympathetic Nervous System (PNS), our "rest and digest" system that is activated during recovery from stress, and (2) positive changes in affect, or emotional states.

In support of SRT, physiological measurements and self-report measures have shown faster stress recovery and improved mood with exposure to natural environments versus urban environments. For example, studies have demonstrated lower self-reported stress (Beil & Hanes, 2013; Roe et al., 2013), greater positive affect (Beute & de Kort, 2014; Bratman et al., 2015; Lee et al., 2014), improved immune functioning (Li et al., 2008, 2011), and reductions in stress-related hormones (i.e., cortisol; Beil & Hanes, 2013) following exposure to natural environments. Some studies have found decreased HR (Laumann et al., 2003; Lee et al., 2014) and decreased blood pressure (Hartig et al., 2003; Li, 2010) after viewing nature imagery or taking walks in nature, although other studies have reported no significant changes in these measures (Brown et al., 2013; Gladwell et al., 2012).

Additionally, correlational studies have determined greater well-being (Grinde & Patil, 2009; White et al., 2013), lower levels of health inequality (Mitchell & Popham, 2008), and lower incidences of morbidity, especially depression and anxiety (Maas et al., 2009), in people who live close to areas high in green space compared to people who live in areas that are low in green space. One study even found shorter hospital stays in rooms with nature views compared to rooms without these views (Ulrich, 1984). Taken together, this literature suggests that both access and proximity to restorative environments may have an impact on short-term stress recovery and long-term cardiovascular health.

1.2 | Vagal tone reflects central modulation of the periphery

The vagus nerve links the central and peripheral nervous systems through neural regulation of the heart (Porges, 1995). Resting vagus nerve activity, or vagal tone, has been used as a measure of cognitive, emotional, and self-regulation. Vagal tone can be indirectly captured through indices of vagally mediated HR variability (vmHRV), which is thought to isolate the parasympathetic influence on the heart (Task Force of the European Society of Cardiology, 1996). Indices of vmHRV such as Respiratory Sinus Arrhythmia (RSA) are known to be reliable measures that capture variation in heart rate in synchrony with respiration, by which the beat-to-beat intervals are shortened during inspiration and expanded during expiration. Low resting RSA, or having too "fixed" a HR interval, is associated with poor regulation of the stress response and self-regulatory behaviors. In contrast, high resting RSA reflects greater variability among HR intervals and is associated with efficient regulation of stress and behavior in response to environmental demands (Porges, 1995, 2007; Smith et al., 2020; Thayer et al., 2009).

The current study examines changes in resting RSA and HR before, during, and after prolonged immersion in nature. Recent studies have found evidence of greater activity in measures of vmHRV following exposure to nature imagery (Beute & de Kort, 2014; Brown et al., 2013; Gladwell et al., 2012) and nature walks (Lee et al., 2014) compared to their urban equivalents. Findings from these recent studies are consistent with Ulrich et al. (1991) hypothesis that activation of the PNS is necessary to facilitate recovery of stress. However, there is limited research on how longer durations in nature may affect the autonomic nervous system activity. We hypothesized that immersion in nature would increase resting RSA and decrease HR compared to a control testing environment before and after immersion.

In line with SRT, this study also assesses changes in self-reported mood and self-reported stress with the expectation that nature exposure would improve mood and reduce stress. Due to the positive relationship between RSA and social support (Kok & Fredrickson, 2010; Smith et al., 2011, 2020; Uchino et al., 2020), a self-report measure of social connectivity was included to examine as a potential covariate. Similarly, we included self-report measures of exercise and sleep disturbance, as well as an objective measure of blood glucose levels, which could have a metabolic influence on the physiological measures of interest (Hall et al., 2004; Sandercock et al., 2005; Singh et al., 2000). For example, blood glucose levels are inversely associated with measures of vmHRV in diabetic patients (Frattola et al., 1997; Rothberg et al., 2016; Singh et al., 2000). By administering these measures, we can examine how these factors influence our results.

2 | MATERIALS AND METHODS

2.1 | Participants

Participants were recruited from a preexisting upper level psychology course (Trip 1) and from flyers around the University of Utah campus and the greater Salt Lake City community advertising a paid research trip designed for this study (Trips 2 and 3). A total of 67 participants (33 male, 31 female, 2 transgender, and 1 other/nonbinary) were recruited across the three trips (Trip 1: $N = 19$, Trip 2: $N = 22$, Trip 3: $N = 26$), with an age range of 18–46 ($M = 25.58$, $SD = 6.27$). A majority of participants (90%) identified as White, Non-Hispanic, 6% identified as Hispanic/Latino, 1% identified as Pacific Islander, 3% identified as Black/African American, 1% identified as Native American/Alaska Native, and 1% identified as Other. There were no significant differences in demographic variables between the three trips.

2.2 | Study design

Our experiment involved a quasi-experimental, within-subjects design, with all participants completing a 5-day nature trip in Bluff, UT. All participants completed three, 2-hr sessions to assess changes in electrocardiography (ECG), blood glucose, and self-report measures. The three sessions took place up to 2 weeks before (pre-testing), during days 2–4 of the trip (desert testing), and up to 2 weeks after (post-testing) the 5-day nature trip. Repeated measures from the three sessions was the within-subjects factor. We collected three administrative waves of this study via the three trips, as trip logistics did not permit a large sample within a single trip. Every effort was made to keep trips identical. When in nature, participants completed the same low to moderate intensity hikes at the group's pace (one hike per day ranging from 2–5 miles roundtrip). Aside from hiking, participants relaxed at the campground (e.g., reading, journaling, and swimming) and completed their research testing session at their designated day and time. As part of the class for the first trip, educational content was provided at night around the campfire.

2.3 | Procedure

At each session, researchers attached ECG electrodes while the participant filled out demographic and self-report questionnaires. All impedances were below 10 kOhms as determined using BIOPAC's EL-CHECK electrode impedance checker. During each testing session, the participants sat in an enclosed, clear pod made by Under the Weather that is designed to protect against wind- and weather-related issues. All data were collected outdoors to control for potential differences in signal-to-noise ratios or any artifacts due simply to being outside. Temperature, time, and weather information were recorded at each session.

Participants first completed a 10-min baseline used to assess resting changes in RSA, followed by several cognitive

FIGURE 1 Pre and post-testing location

FIGURE 2 Desert testing location

tasks that were part of a separate study. Participants were instructed to sit upright in a relaxed state, as well as to minimize movement and to keep their eyes open. Participants were tested at the same time for all three sessions to control for diurnal influences on the dependent variables. All sessions were identical in procedure but differed in the environment and location of testing in the second session (see, Figures 1 and 2). In both the desert and the pre- and post-testing control locations, efforts were made to ensure that there were no people nearby and that participants sat in the pods for the duration of testing. In the control location, participants were set up in the lab and brought outside the psychology building for testing on a concrete terrace, where they could see the building's exterior (see, Figure 1) but did not have a view of nature (i.e., greenery and the surrounding mountain range). In the desert location, participants were set up under a large tent and brought to a sandy riverbank for testing (see, Figure 2). Altitude (control: 4,226 ft; desert: 4,324 ft) and climate (arid desert) were similar across both the control and trip testing locations. The second session took place during the 2nd, 3rd, and 4th days of the 5-day nature trip (due to logistics we were unable to test all participants on the same day).

2.4 | Measures

2.4.1 | Electrocardiography (ECG)

ECG data were recorded using BIOPAC Smart Center (BIOPAC Systems, Goleta, CA, USA). The wireless BioNomadix Smart Center amplified the ECG signal with a 2 kHz per channel maximum sampling rate. ECG data were observed through Acq*Knowledge* (Version 5.0) software. The BioNomadix Smart Center is a small-form data acquisition unit and wireless receiver that connects to a computer USB port and records physiological and data from a wireless transmitter. Physiological data were collected using the lead II configuration to place active electrodes diagonally across the heart (Berntson et al., 2007). Before attaching electrodes, participants were instructed to clean and lightly abrade areas of the skin using alcohol wipes and NuPrep gel. Electrodes were attached at each skin site location using SignaGel.

ECG preprocessing pipeline

ECG data were processed using the Acq*Knowledge* software following standard guidelines for ECG artifact detection and correction (Berntson et al., 1990). ECG recordings were band pass filtered from 0.5–35 Hz. Interbeat interval (IBI) time series were obtained based on the QRS peak detection algorithm developed by Pan and Tompkins (1985), and QRS peaks were marked and kept for analysis. Missing peaks were manually placed and artifacts were edited through visual inspection using the detection algorithm of Bernston and colleagues (1990). Data were epoched into 60 s segments and epochs with unusable contaminated data (e.g., drop in signal) were removed from analyses (see, percentage removed below under data loss). If a file contained over 80% of epochs removed due to issues in the signal, a file was removed from analysis. The Acq*Knowledge* software uses a Fast Fourier Transform with a hamming window function to convert IBIs to the appropriate frequency band for spectral analyses of RSA (defined as 0.15–40 Hz based on recommendations from the Task Force of the European Society of Cardiology, 1996). Frequency domain (RSA) and time domain (HR; beats per minute) parameters extracted from the epochs were then averaged to create overall RSA and HR indices per file.

Data loss

Of the final data set across all three trips with 67 participants, 2 participants were excluded from ECG analysis (1 recording failure and 1 participant did not complete ECG testing). Three additional recordings, one per session, were removed from analysis due to issues in the signal (over 80% of epochs removed). The remaining data set for ECG analysis included 192 recordings from 65 participants across the three sessions, with 64 recordings per session. Of these recordings, there was an average of 0.24 epochs ($SD = 0.79$) removed from the data collapsed across sessions, which equates to 2.4% of data loss due to data contamination. Power analyses using G*Power (Cohen, 1988; Faul et al., 2007) revealed that we were powered at 87% to detect repeated-measures changes based on a medium effect size (Cohen's $d = 0.35$) and our final physiological sample of 65 participants.

2.4.2 | Blood glucose

Blood glucose was measured using the OneTouch Verio IQ glucose testing kit. This measurement was included as a potential covariate in understanding how changes in physiological activity might be influenced by blood glucose levels. Researchers used an alcohol swab to clean the tip of either the fourth or fifth finger of the participant before inserting a disposable lancet into the finger. Researchers collected a 1 μl blood sample onto a glucose test strip, inserted the strip into the glucose reader, and disposed of the testing strip and lancet into a biohazard container.

2.4.3 | Self-report questionnaires

Participants completed a battery of self-report questionnaires to assess changes in exercise, sleep, social connectivity, perceived stress, and mood across the three sessions.

Physical activity scale

The Brief Physical Activity Assessment (Marshall et al., 2005) scale was used to assess changes in moderate and vigorous weekly exercise. Scores were totaled to display an overall physical activity score for each participant, with greater scores reflecting more physical activity.

Sleep disturbance scale

A sleep quality score was calculated by totaling responses to the eight items on the Sleep Disturbances Scale (Yu et al., 2012), in which higher scores reflect greater disturbances, and thus poorer quality of sleep.

Social connectivity scale

Participants completed this short, 2-item scale adapted from Kok and Fredrickson (2010). Items were averaged to obtain a total social connectivity score, with higher scores indicating greater perceived social connectivity.

Perceived stress scale (PSS)

A shortened version of the PSS was used (Karam et al., 2012), consisting of four items that asked participants to rate the extent to which each item applied to them within the past few days. Items were averaged to obtain a total stress score, with higher scores indicating greater perceived stress.

Positive and negative affect schedule (PANAS)

Participants completed the PANAS to assess changes in mood (Watson & Clark, 1999). Participants were presented with a series of words and asked to indicate how they felt about each word at the present moment. These words were categorized and summed into positive and negative affect categories, with higher scores reflecting greater positive or negative affect.

2.4.4 | Quantitative methods

All analyses were conducted in R (version 3.4.2) using the lme4 package (Bates et al., 2012) to determine within-subject changes in RSA, HR, and subjective measures. We used linear mixed-effects models in order to account for repeated measures and random effects on the intercept. We created a three-level session variable (pre-testing, desert testing, and post-testing) as a fixed-effect predictor for the dependent measures of interest. Models were estimated using maximum likelihood and p values were obtained by likelihood ratio tests comparing the model with the session variable against the intercept model. Effect sizes were calculated as Cohen's *d*. Trip wave was also entered as a predictor into each of the models to determine if there were differences by trip. Exploratory Pearson correlation analyses were conducted to determine the association between subjective measures and blood glucose with physiological results. Finally, an exploratory mediation analysis was conducted to examine the relationship between RSA and HR to decouple changes in parasympathetic activity (RSA) and changes in parasympathetic/sympathetic activity (HR).

3 | RESULTS

3.1 | Physiological results

A moderate amount of variance in RSA was accounted for by the clustering of subject (ICC = 0.54). There was a significant omnibus effect of session ($\chi^2(2) = 22.52$, $p < .001$) on RSA (see, Figure 3). There was a significant decrease in RSA from pre-testing to desert testing ($d = -0.54$; See, Table 1) and increase back to baseline from desert testing to post-testing ($d = 0.35$; See, Table 1). There was no significant difference in RSA from pre-testing to post-testing. Average RSA for pre-testing was 7.23 ($SE = 0.15$), for desert testing was 6.5 ($SE = 0.17$), and for post-testing was 6.99 ($SE = 0.16$).

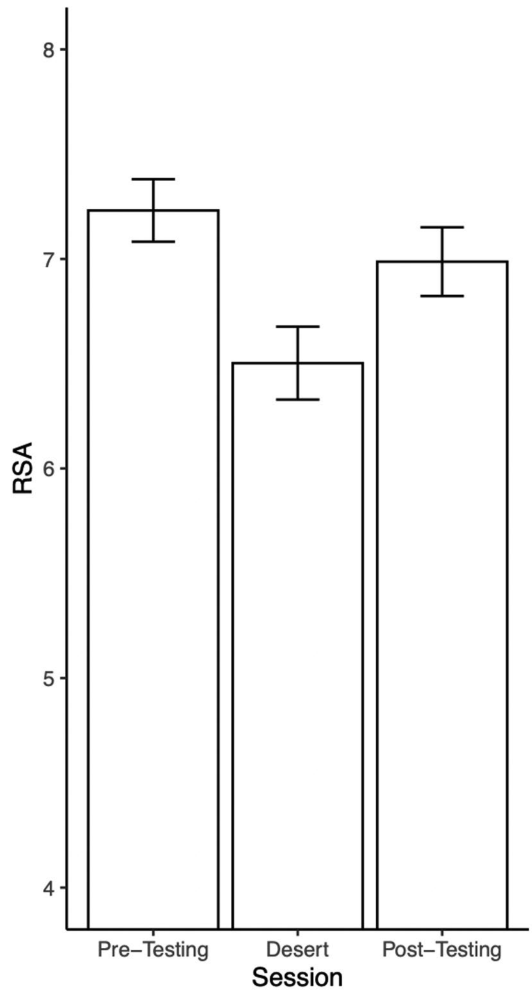

FIGURE 3 Average RSA by testing session. Error bars reflect the standard error of the mean

Results revealed an opposite pattern for HR, with a similar amount of variance that could be attributed to within-subject clustering (ICC = 0.59). There was a significant omnibus effect of session ($\chi^2(2) = 23.12$, $p < .001$) on HR (see, Figure 4).

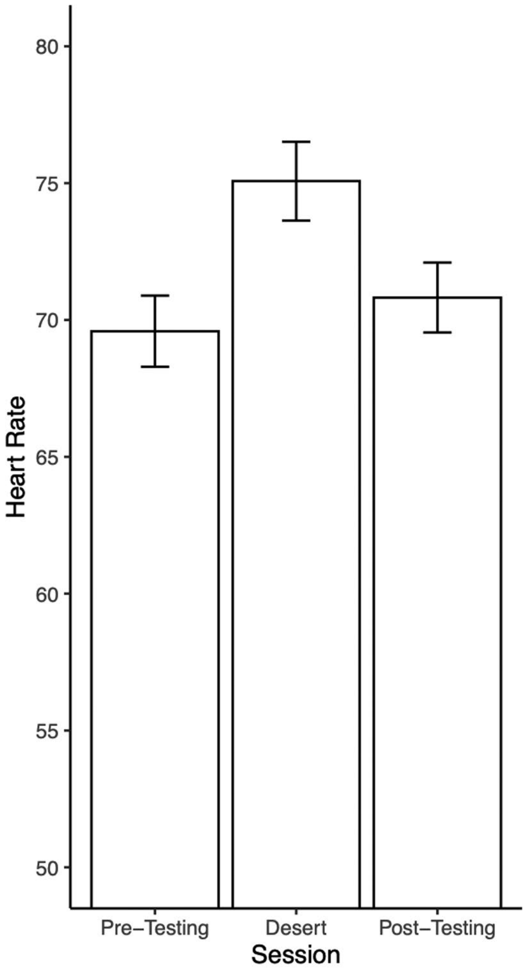

FIGURE 4 Average HR by testing session. Error bars reflect the standard error of the mean

There was a significant increase in HR from pre-testing to desert testing ($d = 0.51$; See, Table 1) and a significant decrease back to baseline from desert testing to post-testing ($d = -0.37$; See, Table 1). There was no significant difference in HR from pre-testing to post-testing. Average HR for pre-testing was 69.6 (*SE* = 1.3), for desert testing was 75.07 (*SE* = 1.4), and for post-testing was 70.82 (*SE* = 1.28). Trip wave was not a significant predictor in these models (p values > .6), suggesting that results did not vary by trip.

3.2 | Blood glucose results

A relatively small amount of variance in glucose level was accounted for by the clustering of subject (ICC = 0.07). There was a significant omnibus effect of session on blood glucose ($\chi^2(2) = 17.90$, $p < .001$), such that there was a significant increase in blood glucose from pre-testing to desert testing ($d = 0.44$, See, Table 2) and a significant decrease in blood glucose from desert testing to post-testing ($d = -0.65$, See, Table 2). Average blood glucose for pre-testing was 106.05 (*SE* = 2.43), for desert testing was 114.81 (*SE* = 2.79), and for post-testing was 101.67 (*SE* = 1.9). Trip wave did not emerge as a significant predictor when entered into the model ($p = .15$), suggesting that results did not vary by trip.

3.3 | Subjective results

3.3.1 | Physical activity

A moderate amount of variance in self-reported physical activity was accounted for by the clustering of subject (ICC = 0.40). There was a significant omnibus effect of session on physical activity ($\chi^2(2) = 9.19$, $p = .01$). There was no

TABLE 1 Coefficients from linear mixed models on physiological measures

	B	SE	*df*	*t*	*p*	CI UL	CI LL
RSA							
Intercept (Pre)	7.23	0.16	115.04	44.6	<.001***	6.91	7.54
Pre-Desert	−0.72	0.15	126.26	−4.84	<.001***	−1.01	−0.43
Pre-Post	−0.25	0.15	126.26	−1.66	.10	−0.54	0.04
Desert-Post	0.47	0.15	125.95	3.18	.002**	0.18	0.76
HR							
Intercept (Pre)	69.52	1.34	107.21	51.89	<.001***	66.89	72.15
Pre-Desert	5.57	1.15	125.70	4.83	<.001***	3.31	7.83
Pre-Post	1.50	1.15	125.70	1.30	.20	−0.76	3.76
Desert-Post	−4.07	1.15	125.42	−3.53	<.001***	−6.32	−1.81

Abbreviations: CI LL, confidence interval lower limit; CI UL, confidence interval upper limit.
*$p < .05$, **$p < .01$, ***$p < .001$.

TABLE 2 Coefficients from linear mixed models on blood glucose and subjective measures

	β	SE	*df*	*t*	*p*	CI LL	CI UL
Blood glucose							
Intercept (Pre)	106.06	2.39	180.53	44.41	<.001***	101.39	110.73
Pre-Desert	8.70	3.24	122.01	2.68	.01**	2.33	15.03
Pre-Post	−4.25	3.25	122.69	−1.21	.19	−10.64	2.12
Desert-Post	−12.92	3.27	121.96	−3.96	<.001***	−19.35	−6.53
Physical activity							
Intercept (Pre)	2.68	0.17	145.29	16.21	<.001***	2.35	3.00
Pre-Desert	0.26	0.18	129.39	1.48	.14	−0.09	0.61
Pre-Post	−0.28	0.17	129.39	−1.59	.12	−0.63	0.07
Desert-Post	−0.54	0.18	129.26	−3.06	.003**	−0.90	−0.20
Sleep disturbance							
Intercept (Pre)	19.24	0.70	138.38	27.44	<.001***	17.87	20.62
Pre-Desert	−0.19	0.72	128.74	−0.27	.79	−1.60	1.22
Pre-Post	−1.42	0.72	129.07	−1.97	.05	−2.83	−0.01
Desert-Post	−1.23	0.71	128.00	−1.73	.09	−2.63	0.17
Social connection							
Intercept (Pre)	4.73	0.17	100.88	27.95	<.001***	4.40	5.06
Pre-Desert	0.23	0.13	127.77	1.8	.08	−0.02	0.49
Pre-Post	0.01	0.13	128.28	0.11	.91	−0.25	0.27
Desert-Post	−0.22	0.13	127.72	−1.68	.10	−0.48	0.04
Perceived stress							
Intercept (Pre)	6.10	0.33	125.17	18.57	<.001 ***	5.46	6.47
Pre-Desert	−1.29	0.32	128.45	−4.15	<.001 ***	−1.9	−0.68
Pre-Post	−0.66	0.32	129.27	−2.09	.04*	−1.28	−0.04
Desert-Post	0.63	0.31	128.36	2.02	.05	0.02	1.24
Negative affect							
Intercept (Pre)	12.57	0.34	107.42	36.97	<.001***	11.90	13.23
Pre-Desert	−1.09	0.29	128.02	−3.77	.002**	−1.66	−0.52
Pre-Post	−0.32	0.29	127.81	−1.13	.26	−0.89	0.24
Desert-Post	0.77	0.29	127.75	2.66	.009*	0.20	1.33
Positive affect							
Intercept (Pre)	27.95	0.92	102.23	30.34	<.001***	24.24	29.15
Pre-Desert	0.55	0.72	128.70	0.76	.45	−0.86	1.96
Pre-Post	−1.94	0.72	129.06	−2.67	.009*	−3.36	−0.51
Desert-Post	−2.48	0.72	128.49	−3.46	.001**	−3.89	−1.08

Abbreviations: CI LL, confidence interval lower limit; CI UL, confidence interval upper limit.

*$p < .05$, **$p < .01$, ***$p < .001$.

significant difference in physical activity from pre-testing to desert testing, but there was a significant decrease in self-reported physical activity from desert testing to post-testing ($d = -0.41$, See, Table 2). Average physical activity for pre-testing was 2.68 ($SE = 0.17$), for desert testing was 2.95 ($SE = 0.15$), and for post-testing was 2.41 ($SE = 0.17$). Trip wave did not emerge as a significant predictor when entered into the model ($p = .18$), suggesting that results did not vary by trip.

3.3.2 | Sleep disturbance

A large amount of variance in self-reported sleep was accounted for by the clustering of subject (ICC = 0.47). There was no significant omnibus effect of session on sleep disturbance. Average sleep disturbance for pre-testing was 19.2 ($SE = 0.73$), for desert testing was 19.07 ($SE = 0.68$), and for post-testing was 17.82 ($SE = 0.69$).

3.3.3 | Social connection

A large amount of variance in self-reported social connection was accounted for by the clustering of subject (ICC = 0.70). There was no significant omnibus effect of session on social connectivity. Average social connection for pre-testing was 4.73 ($SE = 0.18$), for desert testing was 4.96 ($SE = 0.16$), and for post-testing was 4.73 ($SE = 0.17$).

3.3.4 | Perceived stress

A moderate amount of variance in self-reported perceived stress was accounted for by the clustering of subject (ICC = 0.52). There was a significant omnibus effect of session on perceived stress ($\chi^2(2) = 16.45$, $p < .001$). There was a significant decrease in perceived stress from pre-testing to desert testing ($d = -0.47$, See, Table 2), and from pre-testing to post-testing ($d = -0.24$, See, Table 2). There was also a marginally significant increase in perceived stress from desert testing to post-testing ($d = 0.23$, See, Table 2). Average perceived stress for pre-testing was 6.12 ($SE = 0.35$), for desert testing was 4.81 ($SE = 0.32$), and for post-testing was 5.47 ($SE = 0.32$). Trip wave did not emerge as a significant predictor when entered into the model ($p = .42$), suggesting that results did not vary by trip.

3.3.5 | Negative affect

A moderate amount of variance in self-reported negative affect was accounted for by the clustering of subject (ICC = 0.62). There was a significant omnibus effect of session on negative affect ($\chi^2(2) = 14.32$, $p < .001$). There was a significant decrease in self-reported negative affect from pre-testing to desert testing ($d = -0.39$, See, Table 2) and a significant increase from desert testing to post-testing ($d = 0.27$, See, Table 2) but there was no significant difference in negative affect from pre-testing to post-testing. Average negative affect for pre-testing was 12.45 ($SE = 0.34$), for desert testing was 11.46 ($SE = 0.27$), and for post-testing was 12.24 ($SE = 0.39$). Trip wave did not emerge as a significant predictor when entered into the model ($p = .71$), suggesting that results did not vary by trip.

3.3.6 | Positive affect

A large amount of variance in self-reported positive affect was accounted for by the clustering of subject (ICC = 0.67). There was a significant omnibus effect of session on positive affect ($\chi^2(2) = 12.69$, $p = .002$). There was no difference in self-reported positive affect from pre-testing to desert testing, but there was a significant decrease in positive affect from pre-testing to post-testing ($d = -0.25$, See, Table 2) and from desert testing to post-testing ($d = -0.33$, See, Table 2). Average positive affect for pre-testing was 27.78 ($SE = 0.94$), for desert testing was 28.49 ($SE = 0.94$), and for post-testing was 25.94 ($SE = 0.89$). Trip wave did not emerge as a significant predictor when entered into the model ($p = .21$), suggesting that results did not vary by trip.

3.4 | Exploratory analyses

As expected, RSA and HR were strongly and negatively correlated ($r = -0.58$, $p < .001$) such that increases in RSA were associated with decreases in HR. Because we did not have a direct measure of sympathetic activation, mediational analyses were performed to determine the degree to which parasympathetic withdraw accounted for changes in HR to indirectly decouple parasympathetic and sympathetic activity. Notably, the mediation was conducted on coefficients from the pre-testing to desert testing contrast. First, RSA was entered as a predictor in the linear mixed model for HR. RSA emerged as a significant predictor ($B = -5.08$, $SE = 0.44$, $df = 179.06$, $t = -11.53$, $p < .001$ [CI = −5.94, −4.22] in accounting for changes in HR over time. There was still a significant increase in HR from pre-testing to desert testing after controlling for RSA ($B = 1.89$, $SE = 0.89$, $df = 131.70$, $t = 2.12$, $p = .04$ [CI = 0.15, 3.64); however, this variance was reduced from the original model. Multilevel mediation analysis using Bayesian estimation (simulations = 5,000) was performed in R using the mediate package (Tofighi & MacKinnon, 2011) with session (pre-testing to desert testing) as the predictor variable, RSA as the mediator variable, and HR as the outcome variable (see, Figure 5). The indirect effect of RSA on HR was found to be statistically significant (effect = 3.65, $p < .001$ [CI = 2.09, 5.32]), confirming that RSA mediated the relationship between session and HR.

RSA was also positively associated with self-reported exercise, such that increases in exercise were associated with increases in RSA ($r = 0.14$, $p < .05$). However, when entered as a predictor into the model, self-reported exercise did not predict changes in RSA ($p = .22$). HR was negatively associated with self-reported exercise, such that increases in

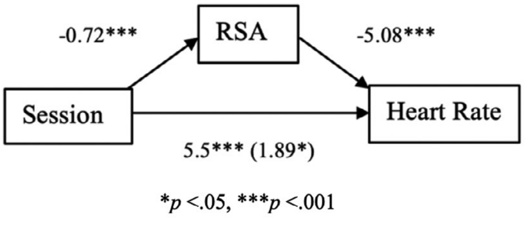

FIGURE 5 Coefficients for the relationship between session and HR as mediated by RSA. The coefficient between session and HR, controlling for RSA, is in parentheses

exercise were associated with decreases in HR ($r = -0.19$, $p < .01$). When entered as a predictor into the linear mixed model, self-reported exercise emerged as a marginally significant predictor of changes in HR ($p = .06$). RSA and HR were not significantly associated with any of the other subjective measures or blood glucose levels (p values > .2).

Temperature (recorded in Fahrenheit) and type of weather (e.g., sunny/partially sunny, windy, cloudy/overcast, etc.) were recorded at each testing session to examine as possible external factors that could be influencing dependent measures of interest. Weather was not significantly correlated with RSA or HR (p values > .24). Temperature was marginally correlated with RSA ($r = -0.13$, $p = .07$) and was significantly and positively correlated with HR ($r = 0.16$, $p < .05$), such that increases in temperature were associated with increases in HR. When entered as a covariate in the linear mixed models, temperature emerged as a significant predictor of changes in HR ($B = 0.12$, $SE = 0.06$, $df = 173.41$, $t = 2.13$, $p = .03$ [CI = 0.01, 0.24]) and a marginally significant predictor of changes in RSA ($p = .06$). However, there was no significant change in average temperature from pre-testing to desert testing ($t = 1.06$, $p = .29$), thus it is unlikely that increases in temperature are driving the decrease in RSA and increase in HR observed in the desert.

Finally, day of testing session (2, 3, or 4 of the 5-day trip) in the desert was examined to determine whether there were differences in average RSA or HR by testing day. Results demonstrated that there was no significant change in average RSA ($F(1, 61) = 0.266$, $p = .645$), or HR ($F(1, 61) = 0.214$, $p = .608$) between the three testing days (RSA: Day 2 – $M = 6.61$, $SE = 0.19$; Day 3 – $M = 6.15$, $SE = 0.34$; Day 4 – $M = 7.08$, $SE = 0.32$; HR: Day 2 – $M = 74.28$, $SE = 2.52$; Day 3 – $M = 75.61$; $SE = 2.48$; Day 4 – $M = 76$, $SE = 1.83$). Furthermore, testing day did not emerge as a significant predictor when entered into the linear mixed models for HR or RSA (p values > .33), suggesting that results did not vary by testing day in the desert.

4 | DISCUSSION

This study was one of the first to examine changes in vmHRV during prolonged immersion in nature. While some studies have found increases in vmHRV after nature walks or viewing nature imagery compared to their urban equivalents (Beute & de Kort, 2014; Brown et al., 2013; Gladwell et al., 2012; Lee et al., 2014), our study found a decrease in vmHRV and an increase in HR while immersed in nature. These findings were contradictory to our hypotheses of a shift toward parasympathetic activity in nature. Although we did not have a direct measure of sympathetic activity, our exploratory mediation analysis suggests that the decrease in RSA from pre-testing to desert testing accounts for most, but not all of the variance involving changes in HR. These findings suggest a shift toward parasympathetic withdrawal and possibly some sympathetic excitation during immersion in nature compared to a control testing environment. Replicating previous research, subjective results showed an improvement in mood and decreased stress in the desert. None of our results varied by trip wave, suggesting these effects replicated across three independent samples. Results from this study are discussed in the context of SRT.

A decrease in RSA has been associated with poor cognitive, emotional, and self-regulation via increased autonomic activation and downregulation of the prefrontal cortex (Porges, 1995, 2007; Thayer et al., 2009, 2012). On our extended trip, participants were removed from their everyday environment and could be experiencing dysregulation while being away from friends, family, and responsibilities as lower RSA is also linked to a lack of social support (Kok & Fredrickson, 2010; Smith et al., 2011, 2020; Uchino et al., 2020). While there was no change in self-reported social connectivity on the trip, future studies could design conditions in an attempt to isolate social influence on nature exposure. However, participants consistently give anecdotal reports of positive experiences on these trips as well as our findings showing improvements in self-reported mood on the trip. As increases in vmHRV are also associated with increases in cognitive demands and recruitment of the prefrontal cortex (Honey et al., 2002; Nikolin et al., 2017; Thayer et al., 2009), a decrease in RSA in nature could reflect downregulation of the prefrontal cortex while participants experience decreased cognitive demands in nature. The increase in blood glucose levels observed in the desert, while unrelated to the physiological measures of interest, may also reflect this downregulation, as studies have found decreased blood glucose levels after participants experience depletion from cognitive and self-regulatory (effortful) tasks (Gailliot & Baumeister, 2007; Hagger et al., 2010; Heatherton & Wagner, 2011). However, this interpretation is subject to mixed findings and appears to be sensitive to task demands, as some studies have found decreases in vmHRV with increasing cognitive workload (Gianaros et al., 2004) and have failed to replicate the link between depletion, glucose, and effort (Hagger et al., 2016).

A shift in sympathetic activity could also be due to positive changes in mood; for example, several studies have found increases in sympathetic activity after participants were presented with film clips or imagery to induce various aspects of positive mood (Christie & Friedman, 2003; Demaree et al., 2004; Giuliani et al., 2008; Mauss et al., 2005; Shiota et al., 2011). However, this literature is mixed, with other studies showing little or even reduced physiological arousal in response to positive mood manipulations compared to negative ones (Cacioppo et al., 2000; Levenson, 1992). Some studies also show increased sympathetic activity due to negative emotions or feelings of threat-based (as opposed to positive) feelings of awe (Cacioppo et al., 2000; Gordon et al., 2017). However, because we observed a significant decrease in self-reported stress and negative affect in nature compared to before or after the trip, it is unlikely that the shift in sympathetic activity found in the desert could be due to an increased presence of negative emotions. Future studies could incorporate a more diverse set of emotion-related measures (e.g., awe and excitement) to further determine how emotion may influence the autonomic activity in nature. Research could also incorporate physiological measures of sympathetic activity (e.g., pre-ejection period; Cacioppo et al., 1994) to corroborate these findings. The dissociation between self-report and physiological measures of stress that we observed in our study is not consistent with SRT, and more research is needed to confirm these effects.

Changes in autonomic activity could also be due to changes in physical activity (Perini & Veicsteinas, 2003; Tulppo et al., 1996). While RSA and HR were correlated with self-reported exercise, exercise did not predict changes in RSA and marginally predicted changes in HR. Furthermore, self-reported exercise did not increase in nature, as there was no difference in self-reported exercise between pre-testing and testing in the desert. It is possible we did not find differences in self-reported physical activity because Salt Lake City is an active city with easy access to hiking and other outdoor activities, and thus participants may have maintained their current level of exercise on the nature trip. Future research should use objective measures of physical activity (e.g., reliable pedometers) to determine the degree to which exercise influences changes in physiology in nature. Experimental designs could also tease apart the relative influence of exercise and nature exposure by having a condition that exercises and a condition that does not exercise in nature, or recruit participants with low versus high levels of physical activity.

Autonomic activity has been linked to attentional intake (Berntson & Boysen, 1987). For example, research suggests that there is an inverted u-shaped relationship between arousal and attention, such that optimal levels of arousal promote attention and increases in task performance, whereas suboptimal and supraoptimal levels are associated with lower levels of attention and worse task performance (Yerkes & Dodson, 1908). Nature contains many stimuli that could capture attention and thereby increase arousal. For example, Ulrich et al. (1991) found increases in HR while viewing a nature video, attributing these results to increases in involuntary (autonomic) attention. Our results may be due to greater levels of involuntary attention in the desert compared to the control testing environment.

The mixed findings on vmHRV in the nature literature could be explained by differences in study design, measurement, and duration of nature exposure. For example, in one study, nature or urban imagery slides were presented *after* a series of cognitive depletion tasks (Beute & de Kort, 2014); in another study nature imagery or urban imagery slides were presented *before* a cognitive task (Brown et al., 2013) which raises the differences in stress recovery versus reactivity. In other studies, vmHRV was assessed during nature imagery or a walk through the forest without the presence of a depletion task (Gladwell et al., 2012; Lee et al., 2014). Likewise, these studies each used different indices of vmHRV, including Root Mean Square of Successive Differences (RMSSD), low frequency (LF) to high frequency (HF) ratio (LF/HF), and HF, which could have different implications for interpretations of vmHRV (Smith et al., 2020). RSA is highly correlated with other time domain (e.g., RMSSD) and HF measures that also isolate the vagal activity (Cacioppo et al., 1994; Grossman et al., 1990), but the interpretation of LF and LF/HF measures as an index of sympathetic activation or the ratio of sympathetic to parasympathetic activation have been refuted, as LF bands are thought to contain both sympathetic and parasympathetic influences (Cacioppo et al., 1994; Moak et al., 2007). Likewise, each of the studies included an urban equivalent, suggesting that differences in vmHRV could also be attributed to specific nature-urban differences. Future research could look at the length, as well as the "level" of nature exposure (nature imagery vs. nature virtual reality vs. real-world nature) on measures of vmHRV. For example, there has yet to be a study examining length of time spent in nature (e.g., short nature walks vs. several days in nature) on physiological measures.

4.1 | Limitations and future directions

Although we attempted to measure potential covariates, such as glucose, social connectivity, exercise, mood, and sleep, there are many dynamic factors that may be changing as a result of nature exposure. From our within-subjects design, we established that changes in RSA and HR appear to be modulated by immersion in nature and are not explained by the other variables we measured. However, nature contains many different types of stimuli (e.g., visual and auditory) and we were unable to tease apart these stimuli in the current study to examine the respective influence of different environmental features in understanding our results. Likewise, it is possible that natural environments may be more cognitively stimulating, rather than something about nature per se that is causing the observed change in autonomic activity. Future research could examine other manipulations that are cognitively stimulating, including artistic or novel scenery, to understand how this aspect may be contributing to these results. Future research should continue to administer a comprehensive battery of measures to determine the degree to which changes in physiology during nature exposure could covary with other factors. Studies could also include an urban trip equivalent to further understand differences between nature and urban environments on vmHRV.

These novel findings imply that exposure to nature may boost mood and enhance arousal. The current research differs from past findings in that it is one of the first to examine the autonomic activity during prolonged immersion in nature and to replicate the results across multiple samples. This research is a critical first step in examining SRT over longer durations of nature exposure and raises important methodological and theoretical considerations for future research.

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AUTHOR CONTRIBUTIONS

Emily E Scott: Conceptualization; Data curation; Formal analysis; Methodology; Project administration; Writing-original draft; Writing-review & editing. **Sara B Lotemplio:** Conceptualization; Data curation; Project administration; Writing-review & editing. **Amy S McDonnell:** Conceptualization; Data curation; Project administration; Writing-review & editing. **Glen D McNay:** Data curation; Project administration; Writing-review & editing. **Kevin Greenberg:** Data curation; Project administration; Writing-review & editing. **Ty McKinney:** Data curation; Project administration; Writing-review & editing. **Bert Uchino:** Conceptualization; Methodology; Supervision; Writing-review & editing. **David L Strayer:** Conceptualization; Resources; Supervision; Writing-review & editing.

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