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A Dose-Response Curve Describing the Relationship Between Urban Tree Cover Density and Self-Reported Stress Recovery

Bin Jiang[1,2], Dongying Li[1], Linda Larsen[1], and William C. Sullivan[1]

Abstract

Although it is well established that viewing nature can help individuals recover from a stressful experience, the dose-response curve describing the relationship between tree cover density and stress recovery is totally unclear. A total of 160 participants engaged in a standard Trier Social Stress Test to induce stress. Participants were then randomly assigned to watch 1 of 10 three-dimensional videos of street scenes that varied in the density of tree cover (from 2% to 62%). Participants completed a Visual Analog Scale questionnaire at three points in the experiment. Analysis revealed a positive, linear association between the density of urban street trees and self-reported stress recovery, adjusted $R^2 = .05$, $F(1, 149) = 8.53$, $p < .01$. This relationship holds after controlling for gender, age, and baseline stress levels. A content analysis of participants' written narratives revealed a similar but even stronger association. These findings suggest that viewing

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tree canopy in communities can significantly aid stress recovery and that every tree matters.

Keywords
dose-response curve, tree cover density, stress recovery, Visual Analog Scale, 3-D visual media

Introduction

Background

Mental stress caused by a variety of social and environmental factors has become a major threat to human health (Lottrup, Grahn, & Stigsdotter, 2013). Mental stress can lead to unhealthy habits, immune system suppression (Cohen, Miller, & Rabin, 2001), and even cardiovascular disease, cancer, stroke, depression, asthma, and other severe health problems (e.g., Aronsson, 1999; Bryant, Harvey, Guthrie, & Moulds, 2003; Childs & Wit, 2009; Dimsdale, 2008; Gump et al., 2011; Mitchell & Popham, 2008; Prince et al., 2007; Roux, 2003; Steptoe & Brydon, 2009).

Fortunately, both theory and empirical evidence suggest that contact with nature can foster stress recovery. Ulrich's stress reduction theory (SRT) posits that exposure to nature supports psychophysiological stress recovery, leading to reduced negative affect and arousal (Bratman, Hamilton, & Daily, 2012; Ulrich et al., 1991). He argued that humans have a genetic inclination to respond positively to environments favorable to survival and safety. A variety of empirical studies have demonstrated that, compared with settings with little or no nature, exposure to settings that contain nature helps people recover more quickly from the psychological symptoms of stress (e.g., Chang & Chen, 2005; Hartig, Mang, & Evans, 1991; Leather, Pyrgas, Beale, & Lawrence, 1998; Parsons, Tassinary, Ulrich, Hebl, & Grossman-Alexander, 1998; Tyrvainen et al., 2014; Ulrich et al., 1991; van den Berg, Hartig, & Staats, 2007; Wells & Evans, 2003).

Although it is well established that exposure to an urban forest has stress recovery effects, the shape of the dose-response curve is entirely unclear. Lack of this knowledge prevents health care providers and public health officials from recommending exposure to urban forests as part of preventive health care or clinical treatment programs. Not understanding the shape and implications of the dose-response curve also costs landscape planners and city managers the opportunity to make science-based management decisions regarding the allocation of resources that might enhance the urban forest and thereby improve the health and longevity of the people they serve.

In this article, we seek to describe the shape of the dose-response curve for how exposure to varying densities of an urban forest impacts recovery from a stressful event. We begin by reviewing theory and evidence regarding stress and human health. Next, we review recent evidence connecting exposure to nearby nature to lower levels of stress. Finally, reporting the results of an experiment involving 160 individuals, we describe a dose-response curve and discuss the implications of the findings for design and planning.

Empirical Evidence

An expanding body of empirical research has shown relationships between contact with natural environments and stress recovery. This evidence comes from studies that use a variety of methods and that engage a variety of populations.

Correlational studies, based on self-reports, consistently find that higher levels of greenness in the built environment have been related to more positive moods and stress recovery. Adults who had greener views from their windows reported calmer feelings (Kaplan, 2001). The impact of life stress was lower among children with high levels of nearby nature than among those with little nearby nature (Wells & Evans, 2003). A nationwide survey of adults in Sweden found that people with access to workplace greenery had lower stress levels (Lottrup et al., 2013). A nationwide survey in the Netherlands found that green space around the home was related to recovery from stressful events (van den Berg, Maas, Verheij, & Groenewegen, 2010), In England, nationwide surveys found that urban residents with more nearby green space had lower levels of mental distress (White, Alcock, Wheeler, & Depledge, 2013) and lower levels of all-cause mortality and mortality related to circulatory disease over a 5-year period (Mitchell & Popham, 2008). In another study, residents living in greener environments reported lower levels of stress and had cortisol levels that were consistent with their assessments (Roe et al., 2013; Ward Thompson et al., 2012). These findings may stem from increased exercise associated with living near green spaces or perhaps from lower levels of stress that people seem to experience when they are in green spaces.

Laboratory studies, which can provide stronger causal claims, have found that exposure to nature leads to faster recovery from stress. These studies have generally used photos or videos of nature as surrogates for actual natural settings. Ulrich and colleagues (1991) found that viewers exposed to a 10-min video of natural settings had greater stress recovery than viewers who watched videos of urban settings, as measured by self-rated affective states and physiological indicators of stress. Similarly, participants who watched a

30-min video of a drive in a natural setting generally experienced a greater stress reduction than those who watched a video of a drive in an urban setting (Parsons et al., 1998). In addition, viewing photographs with greener office window views elicited greater self-reported positive emotional responses and physiological responses indicating stress recovery (Chang & Chen, 2005).

Field studies, in which people engage with particular landscapes, further reinforce the relationship between exposure to nature and recovery from stress. In a recent study, a short visit to an urban woodland or urban park had greater positive impacts on participants' perceived restorativeness, subjective vitality, and mood than did a visit to a built-up city center (Tyrvainen et al., 2014). In another study, participants visited four sites with various levels of naturalness. After spending time in the most natural site, participant's self-reported stress and salivary alpha-amylase levels (Beil & Hanes, 2013) were significantly lower than when they visited the less natural sites. Compared with individuals who visited urban settings, participants who visited forest landscapes reported significantly higher levels of calm and refreshed feelings, and their pulse rate, blood pressure, and salivary cortisol levels were lower, indicating lower levels of stress (Lee, Park, Tsunetsugu, Kagawa, & Miyazaki, 2009). Horticulture therapy significantly reduced cardiac rehabilitation inpatients' negative moods, including anxiety and tension, while regular education classes did not have the same calming effects (Wichrowski, Whiteson, Haas, Mola, & Rey, 2005). Participating in activities in nature may improve stress-related mood status. A meta-analysis of field studies reported a significant reduction in self-reported anxiety level after people participated in activities that took place in natural environments (Bowler, Buyung-Ali, Knight, & Pullin, 2010).

Although evidence supports the prediction that exposure to nearby nature promotes recovery from stress, the shape of the dose-response curve is entirely unclear. Previous studies have not offered a clear picture of the dose-response curve for several reasons. Some studies compare the stress recovery effects of urban and natural landscapes but look at only rather coarse categories of exposure to nature (e.g., Chang & Chen, 2005; Roe & Aspinall, 2011; Ulrich et al., 1991). Although these studies consistently found that greener landscapes help individuals recover from stress faster than more barren landscapes, they do not provide information regarding how varying densities of tree cover impact recovery from stress. Other studies compare different kinds of urban spaces rather than focusing on a specific type, such as neighborhood streets or school yards (Beil & Hanes, 2013; Hernandez & Hidalgo, 2005). These studies also do not compare varying densities of tree cover. Other studies report on the impact of varying densities of tree cover. But in these studies, only a limited range of tree density has been examined, which makes it

Figure 1. Panoramic photographs of two 3-D videos with a low (top, 2%) and a high (bottom, 61%) eye-level tree cover density.

difficult to identify a comprehensive dose-response curve (Beil & Hanes, 2013; Kuo & Sullivan, 2001).

Thus, we are left to wonder: Is a little exposure to nearby nature enough to produce calming effects from a stressful event? Do higher densities of nearby nature elicit greater stress recovery? Is the relationship linear, or does the effect lessen with greater and greater amounts of vegetation? Does the relationship between tree cover density and stress reduction hold when controlling for other potential predictors of stress recovery, such as age, gender, and baseline stress level? Do narrative experiences from the videos complement the findings from stress reduction measures?

In this study, we examine the relationship between exposure to various levels of tree density along single-family residential streets and reductions in self-reported stress.

Method

Nature Treatments

To simulate exposure to nature in this laboratory experiment, we created ten 6-min three-dimensional (3-D) videos of neighborhood streets that varied in the eye-level tree cover density from approximately 0% to 70% (Figure 1). Participants viewed the 3-D videos through a 3-D personal viewer (Sony HMZ-T1; Figure 2).

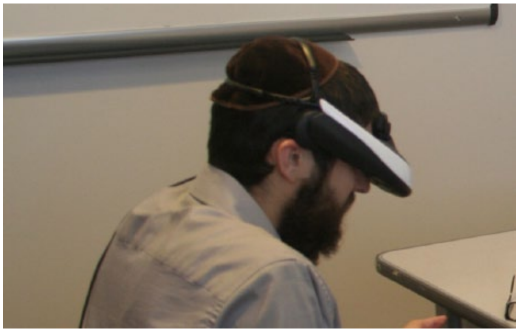

Figure 2. Watching a 3-D video through a 3-D personal viewer (Sony HMZ-T1).

To make the videos, we first identified hundreds of residential streets with varying tree density in four Midwestern metropolitan areas: Champaign–Urbana and Springfield, Illinois; Indianapolis, Indiana; and St. Louis, Missouri. We used several steps to limit the physical characteristics besides the density of the trees among sites. First, we selected residential streets that had a median annual income per household between US$50,000 and US$75,000 at the block group level (data from Google Earth Pro). After this step, we visited 255 candidate streets.

At each candidate site, we mounted a 3-D camera (Sony HDR-TD10) on a tripod and positioned it at the edge of the street next to a driveway. Filming locations did not have a tree or similar structure within 10 meters of the front of the camera.

We then shot video by smoothly panning about 150 degrees in a clockwise motion for 25 to 30 s. Each shot was repeated 5 times, and the smoothest shot without detectable friction or waggle and with the least changes in sunlight intensity was selected. All videos were taken on sunny days without strong winds in middle to late summer (July 1 to September 10, 2011). Videos were shot between 10:00 a.m. and 3:30 p.m. to reduce inconsistencies of shadows and sun angles (Ulrich et al., 1991). In an effort to keep distractions at a minimum and limit confounding physical characteristics, we waited until there were no people, animals, or moving vehicles present in the viewshed when we filmed the videos.

Next, we used a 3-D video-editing software (Sony PMB) to extract a panoramic photo from each of the resulting 255 videos that represent the entire viewshed of each video. Three experts in landscape architecture evaluated

Table 1. Range and Mean of Tree Cover Density (%) of 10 Street Scene Videos.

Video	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
Range	0-2.5	2.6-5.0	5.1-7.5	7.6-10.0	10.1-20.0	20.1-30.0	30.1-40.0	40.1-50.0	50.1-60.0	60.1-70.0
M	1.7	3.8	6.1	8.9	14.9	24.0	35.7	44.4	54.1	62.0
SD	1.2	0.1	0.9	0.9	3.7	3.6	1.9	3.6	2.4	0.7

Note. Each video contains five video clips for five community streets.

the photos. Their goal was to eliminate any street scene that contained unusual elements such as a unique looking building, unusual or outstanding plants, animals of any kind, unusual architectural decorations, vehicle traffic, the absence of a sidewalk, or distinct weather conditions. Each expert identified a list of panoramic photos that were considered unsuitable. The photos rated as unsuitable by more than one researcher were dropped from the pool. Then the experts discussed the suitability of the photos that received one vote. Experts further reviewed videos of remaining sites to remove videos containing moving people, cars, or animals from the sample pool. Based on this evaluation, we removed streets with dramatic physical characteristics from the sample pool, leaving 50 street scenes for this study.

Using 3-D video-editing software (Sony Vegas Pro 10), we created a 36-s video clip for each site. To create the videos, we combined 36-s sections of five sites with the same density of tree cover and played each section in a clockwise and a counter-clockwise direction. Ten 6-min videos, each with a different level of tree cover, were created.

Tree Cover Density

In each of the panoramic photos, we used the Magnetic Lasso Tools (MLT) of Photoshop CS5 to select the tree canopy and tree trunk area and then used the histogram function to identify the number of pixels that were associated with trees and those that were not. We then divided the number of pixels occupied by trees by the total number of pixels in the image and multiplied this number by 100 to obtain our measure of tree cover density. To our knowledge, this is the first study to calculate tree density in this way. Table 1 describes the tree cover density associated with each of the 10 videos.

It is possible that the green features other than tree cover—such as lawns, shrubs, and flowers—were significantly different among the sampled panoramic photographs. If that were the case, these other green elements might impact people's stress response and alter the relationship we seek to measure between tree cover density and stress recovery. To examine this possibility, we followed the same procedure described above to measure the percent of each photo that included non-tree vegetation–herbaceous plants, shrubs, lawns–and then conducted a one-way ANOVA to see if there were any differences in these other forms of vegetation for the 10 categories of street scenes. We found no significant differences in the percent of other green features among the 50 video clips, $F(9, 40) = 1.54$, $p = .17$. This finding implies that the amount of green landscape features other than trees did not significantly vary among video clips. Thus, we examined tree cover density as the sole indicator of greenness in this study.

Stressor

To induce psychological stress, participants took a Trier Social Stress Test (TSST) that included 3 min to prepare a public speech, a 5-min public speech, and a 5-min subtraction task performed in front of two interviewers and a video camera, and completed without paper and pencil or a calculator (Kirschbaum, Pirke, & Hellhammer, 1993). To increase stress levels, interviewers told participants that their performance would be recorded and assessed later, but in fact, no video recording was made.

We used the Visual Analog Scale (VAS) to measure self-reported stress levels 3 times during the experiment. The VAS has been widely used in clinical research as a method for rating subjective phenomena (Childs, Vicini, & De Wit, 2006; Kirschbaum et al., 1993; Lara-Munoz, de Leon, Feinstein, Puente, & Wells, 2004). Compared with other methods with a set of restricted options, the VAS provides greater sensitivity for measuring perceived stress and more freedom to depict subjective experiences (Marsh-Richard, Hatzis, Mathias, Venditti, & Dougherty, 2009). In previous studies involving the VAS, researchers have used a wide variety of stress indices or subjective indicators of stress. For instance, Childs et al. (2006) used "anxiety," "uneasy," "jitteriness," "stimulation," and "calmness" as indicators of stress. To measure participants' stress while keeping the burden of reporting their stress level low, we used a modified version of von Dawans's Trier Social Stress Test for Groups (TSST-G) VAS protocol with the indices "anxiety," "tension," and "avoidance" (von Dawans, Kirschbaum, & Heinrichs, 2011). We asked participants to focus on each term and tell us the extent to which they "have that feeling now." The questionnaire consisted of three 10-cm horizontal lines; one each for anxiety, tension, and avoidance. The left end of the line was marked "not at all" (0) and the right "extremely" (100). After hearing the instructions, participants placed a mark (X) on each line indicating the degree of stress they felt at that moment. By measuring the distance from the left end of the scale to the mark, we identified the value for a specific VAS index.

Participants

We recruited 160 healthy adults, and 158 completed the experiment: 80 men, 78 women. Their age range was 18 to 32 (M = 21.20, SD = 2.67). To mitigate the influence of cultural differences on stress responses, only individuals who had lived in the United States for at least 18 years were included. Individuals with a medical history of diagnosed depression or posttraumatic stress disorder were excluded from the experiment.

Experimental Procedure

All participants took the experiment between 2:30 p.m. and 5:30 p.m. during summer 2012. In the waiting room, a receptionist made a standard introduction to the experimental procedure and devices. The receptionist then explained the VAS questionnaire to ensure that each participant had an understanding of the three items (anxiety, tension, and avoidance) and how to mark the VAS scales. Then, participants gave informed consent and completed a health form to ensure that they had no major health conditions or drug use that would influence the research results.

During the experiment, each participant sat across a table from two interviewers. Before the experiment began, participants rested for 3 min. After their rest, they filled out the first VAS questionnaire (T1: *baseline*). Next, they participated in the TSST and then immediately completed a second VAS questionnaire (T2: *stressed*).

Each participant was then randomly assigned to watch one of the ten 3-D community street videos. After the videos, participants once again completed the VAS questionnaire (T3: *recovered*) and then relaxed for 3 min. Finally, each participant was given up to 15 min to write a narrative about their feelings during the experiment in a text box on a computer in another quiet room (see summary timeline of procedures in Online Appendix Figure A). We used these narratives to further explore stress recovery effects of the nature treatment.

Results

Results are presented in five sections. First, we address the challenge of having outcome data that are skewed. We then explore whether the TSST created feelings of stress in the participants. Next, we examine the shape of the dose-response curve for density of trees on stress recovery through a simple linear regression and two curvilinear models. In the next section, we address the potential impacts of age, baseline stress level, and gender on the relationship between tree cover density and stress reduction. Finally, the VAS results are checked against the participants' written narratives.

Stress Reduction

The scores on reported stress levels are right skewed, and the standard assumptions of regression were violated, so we made a log transformation of the original measures of the stress scores to reduce kurtosis. The transformed data prove to be normally distributed, and the homogeneity of variance holds. The three VAS stress indicators of anxiety, tension, and avoidance were internally consistent (Cronbach's $\alpha = .80$); for each analysis outliers (± 2 *SD*) were omitted.

Stress reduction was calculated by subtracting the stress level measured after watching the 3-D videos ($VAS_{T3recovered}$) from the stress measured at the end of the TSST procedure ($VAS_{T2stressed}$). We followed this procedure for each component of stress—anxiety, tension, and avoidance. We also created a summary stress score by calculating the mean of the three component scores.

After a logarithmic transformation of the raw data, we used the standardized mean-change statistic (d) to estimate the effect size of the change in stress status. The d value has been widely used as an index for repeated measures effect size estimates (Dickson & Kemery, 2004). An effect size of .20 is considered small, .50 is moderate, and .80 or greater is large.

$$d_{\text{stress arousal}} = \frac{\left(M_{\text{T2stressed}} - M_{\text{T1baseline}}\right)}{SD_{\text{T1baseline}}}.$$

$$d_{\text{stress reduction}} = -\frac{\left(M_{\text{T3recovered}} - M_{\text{T2stressed}}\right)}{SD_{\text{T2stressed}}}.$$

Effectiveness of the Stressor

To what extent did the mock job interview speech and mental subtraction task (the TSST) produce a stress response in our participants? To address this question, we conducted paired t tests on mean values of anxiety, tension, and avoidance levels immediately before and after the TSST (Table 2). Results show that the TSST did yield a significant increase in self-reported summary stress scores as well as its components of anxiety, tension, and avoidance. These results confirm that the TSST is an effective laboratory stressor.

Table 2. Self-Reported Measures of Stress and Its Three Constituent Measures Before and After Participants Were Exposed to the TSST.

	Summary stress	Anxiety	Tension	Avoidance
Baseline time (T1)				
M	−.22	−.12	−.14	−.38
SD	.65	.68	.73	.80
Stressed time (T2)				
M	.45	.54	.54	.27
SD	.46	.38	.45	.74
Comparison (T1 − T2)				
M	−.67	−.66	−.68	−.65
SD	.62	.65	.75	.78
t	−13.19****	−12.36****	−11.04****	−9.95****

Note. Data were presented here after the log transformation.
****$p < .0001$.

The Dose-Response Curve

Because we did not posit a hypothesis describing the relationship between tree cover density and stress recovery, we begin our analysis of the dose-response curve by presenting a scatterplot of the data. As can be seen in Figure 3, we fit the scatterplot with a locally estimated scatterplot smoothing (LOESS) curve to initially visualize the dose-response trend. In general, LOESS is a local regression method that fits the data through a smooth curve. The curve is calculated through a linear least squares or nonlinear regression model for several subsets of data.

The LOESS line in Figure 3 shows a positive, linear trend. The analysis of the scatterplots and smoothers implies that the association between tree cover density and stress recovery is a linear relationship in which the greener a setting, the greater the stress reduction. To test this possibility, we conducted a simple regression with tree cover density as the independent variable and the stress reduction from the end of T2 (stressed) to T3 (recovered) as the dependent variables (Table 3). Results from these ordinary least squares (OLS) regressions indicate that the dose-response curve can be explained by a linear regression equation. The summary measure of participants' self-reported stress reduction and also the three separate measures (tension, avoidance, and anxiety reduction) have significant, positive linear relationships with tree cover density, adjusted $R^2 = .05$, $F(1, 149) = 8.53$, $p < .01$, $y = .012x + 1.172$.

Although the LOESS curve suggests a linear relationship between tree cover density and stress recovery, it is still possible that the relationship is

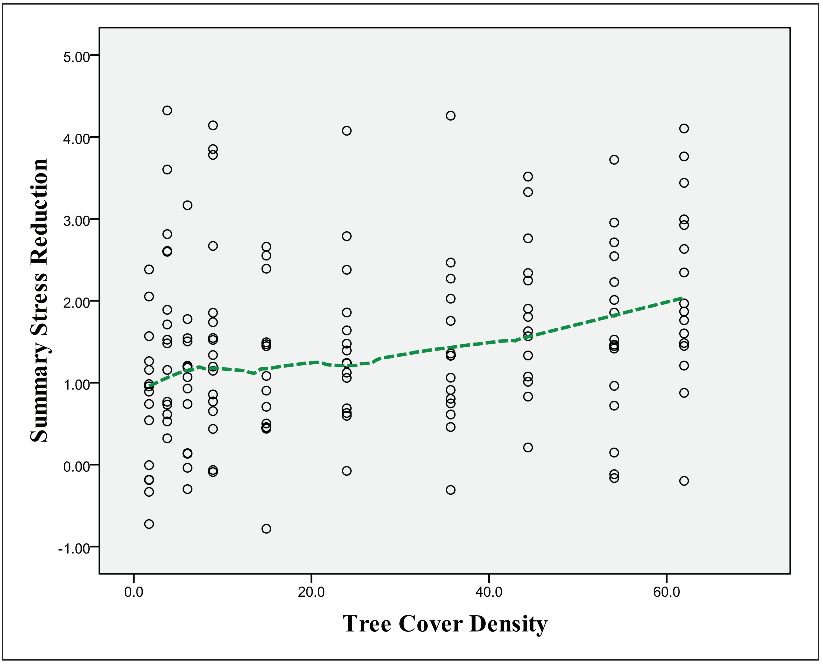

Figure 3. Summary stress and tree cover density: LOESS curves and scatterplots of log-transformed data.
Note. LOESS = Locally Estimated Scatterplot Smoothing.

Table 3. Comparison of Linear and Curvilinear Regression Models for the Relationship Between Tree Cover Density and Measures of Self-Reported Stress Reduction After Participants Viewed the Nature Treatment Video.

	Summary stress			Tension		Avoidance			Anxiety		
	R^2	*F*	BIC	R^2	*F*	R^2	*F*	BIC	R^2	*F*	BIC
Linear	.05**	8.53	25.14	.02*	3.76	.03†	5.92	−64.15	.04**	7.33	94.00
Quadratic	.05*	4.38	27.14	.01	1.92	.03†	2.94	−62.15	.03*	3.64	96.00
Cubic	.04*	3.16	27.63	.01	1.27	.02	1.95		.03†	2.42	98.00

Note: BIC values were calculated only if there were at least 2 *p* values were less than .1 for the same measure. R^2 values presented in this table are adjusted R^2 values. BIC = Bayesian Information Criterion.
†$p < .1$. *$p < .05$. **$p < .01$.

Table 4. Regression Coefficients for Models Predicting the Summary Measure of Stress Reduction and Its Three Constituent Measures.

	Model 1	Model 2	Model 3	Model 4
	Summary stress reduction	Tension reduction	Avoidance reduction	Anxiety reduction
	β	β	β	β
Tree cover density	.21**	.14†	.24**	.20**
Age	−.14†	−.08	−.15†	−.19**
Male	−.11	−.11	−.15†	−.09
Baseline stress level	−.30***	−.28***	−.15†	−.37****
Adjusted R^2	.15	.10	.11	.20
F	7.72****	5.02***	5.24***	1.20****
n	151	147	143	150

Note. For Models 1 through 4, baseline stress levels were for baseline values of summary stress, tension reduction, avoidance reduction, and anxiety reduction, respectively.
†$p < .1$. *$p < .05$. **$p < .01$. ***$p < .001$. ****$p < .0001$.

better explained by more advanced polynomial regression models. To test that possibility, we conducted a quadratic and a cubic regression analysis, and the results are presented in Table 3.

Results of the quadratic regression analysis show that anxiety reduction and summary stress reduction have significant associations with tree cover density. Avoidance reduction has a marginally significant association with tree cover density. Results of the cubic regression analysis show that only the summary stress reduction has a significant cubic relationship with tree cover density. Anxiety reduction has a marginally significant cubic relationship with tree cover density. It is hard to tell which model is most appropriate if we only compare adjusted R^2 and p values among the linear, quadratic, and cubic models.

To identify which curve fits the data best, we calculated and compared Bayesian information criterion (BIC) values for all significant or marginally significant linear, quadratic, and cubic models for each measure of stress reduction. Results in Table 4 show that all linear models have the lowest BIC values and contain the lowest number of parameters. Thus, we conclude that, compared with quadratic and cubic models, the linear model best explains the dose-response relationship for the summary measure of stress reduction and the three constituent measures. Compared with watching a 6-min video with 2% tree cover density (d = 1.20), watching a similar video with 62% tree cover density resulted in 60% increase in stress recovery ($d = 1.92$; see Online Appendix Figure B).

Confounding Factors

To assess whether the linear relationship between tree cover density and stress reduction is robust, we added additional predictors to four OLS regressions (Table 4). Specifically, age, gender (female = 0, male = 1), and baseline stress level were added to the equations for the four stress measures, along with the 10-level tree cover density measure. In each case, the multiple regression models yield significant results. Notice that, in each case, after controlling for age, gender, and baseline stress level, the density of the tree cover still holds its positive linear relationship for the summary stress reduction and its three constituent measures (Table 4). Specifically, the association is significant for summary stress ($p < .01$), anxiety reduction ($p < .01$), and avoidance ($p < .01$). The association is marginally significant for tension ($p < .10$).

Gender, age, and baseline stress level show different effects in the models. Gender is not related to summary stress reduction, tension reduction, and anxiety reduction, and only marginally related to avoidance reduction ($p < .10$). Age has a much stronger relationship: younger participants experienced greater anxiety reduction ($p < .01$) and a marginally greater summary stress reduction ($p < .10$) and avoidance reduction ($p < .10$). Participants with greater baseline stress levels experienced less stress reduction: individuals who reported higher levels of stress in their lives experienced marginally less reduction in avoidance reduction ($p < .10$) and significantly less reduction in the other three measure ($p < .001$ or $p < .0001$). Furthermore, several interaction terms, including Age × Tree cover density, Gender × Tree cover density, and Baseline stress × Tree cover density, were also tested in the models. None of the interaction terms, however, were significant.

Participants' Narratives

To what extent do the written narratives help explain the dose-response curve of tree cover density to stress recovery? To address this question, we conducted a content analysis that examined the categories and themes that emerged from the responses. Among the 160 participants of the study, 144 (90%, 75 women, 69 men) wrote narratives reporting their feelings while watching the videos. Working together and without knowledge of which video each participant saw, three experts in landscape architecture reviewed all narratives and identified keywords from the text that mentioned any aspect

Table 5. Keywords Used by Participants to Describe Their Experience of Stress Recovery.

Theme	Keywords
Stress recovery experience	Relaxing, calming, tranquil, at ease, comfortable, peaceful, serene, settled, safe, quite, a reprieve, mesmerizing, soothing, pleasant, unrushed, undisturbed, enjoyable, worry-free.

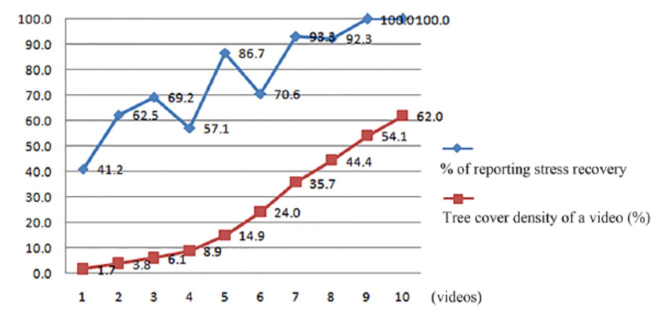

Figure 4. The relationship between tree cover density and percent of participants who reported the stress recovery effect for each of the 10 videos.

of stress recovery. Such comments are summarized in Table 5. Then, for each tree cover density, we counted the number of participants who mentioned that they felt calm or relaxed while watching the videos.

Figure 4 shows that the percent of people using keywords indicating stress recovery increases as the density of tree cover increases. At the lowest level of tree density (mean of 2%), only 41% of participants reported a calming effect. As tree cover density reached 36%, more than 90% of participants reported a stress recovery experience. All of the participants who watched the two videos with the highest tree cover density reported a stress recovery experience. Compared with watching a 6-min video with 2% tree cover density, watching a similar video with 62.% tree cover density resulted in a 143% increase in the percentage of people reporting stress recovery. Thus, the results of the participant's narratives made after watching the video are consistent with the results from the VAS findings showing that increases in tree cover density predict systematically faster recovery from a stressful experience.

Discussion

This study describes a statistically reliable dose-response curve for the impacts of viewing community street videos with varying tree densities on self-reported stress recovery. The curve is a positive, straight line, indicating that videos containing higher levels of tree density elicit greater self-reported stress reduction. This finding is supported by both quantitative data obtained from the VAS questionnaire and qualitative data obtained from the written narrative made by participants.

A Dose-Response Curve

The most important contribution of this work is the depiction of the dose-response curve: We identify a positive, linear dose-response curve indicating that an increase in tree density yields greater self-reported stress reduction. Compared with watching a 6-min video with 2% tree cover density, watching a 6-min video with 62% tree cover density resulted in 60% increase in stress recovery. This relationship holds after controlling for gender, age, and baseline stress levels.

Although a growing amount of empirical work has consistently shown that greener landscapes are associated with less self-reported stress or greater recovery from stress in individuals of both sexes and of different ages, and socioeconomic status (e.g., Beil & Hanes, 2013; Chang & Chen, 2005; Grahn & Stigsdotter, 2003; Lottrup et al., 2013; Ward Thompson et al., 2012), a variety of constraints have prevented scholars from identifying a comprehensive, detailed dose-response curve. To overcome these obstacles, we developed a research design that may be helpful for future researchers seeking to further explore the dose-response curve: First, this study focused on a specific type of urban space, neighborhood streets within single-family communities. This single land use removed variability in the presentation of the scenes, leading to greater confidence in the outcome. Second, the range of tree cover density varied from 2% to 62% in the videos we created. This span of tree cover density allowed us to create a complete profile of the dose-response curve for this setting (it is rare to find a community street with tree cover density above 63%).

These steps increase the validity of our findings, but also decrease their generalizability. Because we examined only one type of urban space, the neighborhood street corridor of medium-income, single-family neighborhoods, it is unclear how these findings generalize to other kinds of built spaces. Future research should examine a variety of other settings such as urban streets in poor neighborhoods, urban parks, schools, campuses, and hospital gardens across the urban, suburban, and rural spectrum, and within different socioeconomic contexts to test whether the relationship identified in this study is influenced by geographical, physical, and social contexts. Second, participants in this study were healthy, young adults who have lived in the United States for at least 18 years. Future research should recruit participants with a wider range of age, health status, socioeconomic, and cultural backgrounds to investigate how doses of tree cover density influence self-reported stress recovery across various population groups. Third, self-reported stress is only one way to measure stress responses. It is important for future research to investigate the dose-response curve using physiological measures, such as cardiovascular responses, hormonal responses, muscle tension responses, and body temperature responses. Fourth, this study examined street scenes that included common tree species in the Midwestern United States. We did not include scenes that showed trees with distinct colors, shape, or textures. Our objective in excluding trees with unique features was to reduce sources of variability that might impact the findings. Future research should explore factors that we did not address here (e.g., biodiversity, the cultural meaning of trees) on stress recovery so that we have a more complete picture of the impact of varying density of trees on human well-being.

In sum, this study describes a comprehensive, detailed dose-response curve for the impacts of viewing videos with varying densities of tree cover on self-reported stress reduction. Although 6-min videos of community street scenes elicited a small effect on stress recovery, the effect was systematically positive and significant. There is evidence suggesting that the impacts we measured here will be greater for individuals who actually live in settings similar to the ones we measured here and who thus experience these tree cover densities on a regular basis (Kahn et al., 2008; Kahn, Severson, & Ruckert, 2009). The results presented here can help landscape architects, planners, and city managers justify a greater investment in urban street trees.

Visual Analog Scale

This study is one of the first in the field of environment and behavior to use the Visual Analog Scale (VAS) to measure participants' stress responses to urban landscapes. Numerous studies in environment and behavior research have used verbal or numeric rating scales, perhaps making them seem like safer choices than VAS. In clinical studies, VAS has been widely used and is a reliable method for rating subjective responses such as pain, mood, and anxiety (Marsh-Richard et al., 2009). Several studies find that the VAS more accurately represents standard stimuli than verbal and numeric rating scales with restricted options because it allows individuals to mark any point on a scale with predetermined length and direction (Lara-Munoz et al., 2004; Marsh-Richard et al., 2009). Significant differences of reported stress status at different time points and a wide range of reported stress levels make VAS a reliable and sensitive tool to measure stress responses to laboratory stressors and visual landscapes. VAS is also easy to understand, requires little mental effort, and takes very little time to complete. Given these advantages, other researchers in our field may find the VAS to be productive and useful tool.

3-D Video

Another innovation in this study was the use of 3-D videos rather than 2-D videos or photographs as surrogates for real landscapes in environment-behavior research. Many previous studies have shown that 2-D photographs (e.g., Chang & Chen, 2005; Kuo, Bacaicoa, & Sullivan, 1998) and 2-D videos (e.g., Parsons et al., 1998; Ulrich et al., 1991) are reliable surrogates for real landscapes because they successfully evoke participants' physiological and psychological healthy responses. 2-D photographs and videos can also control for environmental attributes in studies that seek to identify the relationship between varying environmental features and some outcome. 3-D videos share the advantages of 2-D imagery while also providing a more immersive experience for the viewer. We used a 3-D video camera (Sony HDR-TD10) to record existing community street scenes and then used a 3-D personal viewer (Sony HMZ-T1) to give participants an immersive experience within a laboratory room that was similar to watching a 3-D movie within a standard film theater. The level of immersion that 3-D video allows may be attractive to other scholars who seek to understand the impact of environmental features on individuals.

Because 3-D video technology has not been widely used in environment-behavior research, more evidence is needed to further verify its validity. Only one study has examined an individual's response to a 3-D, simulated landscape setting (Valtchanov, Barton, & Ellard, 2010). Future research might examine differences in responses as participants are exposed to a real landscape, a 2-D video, and a 3-D video of the same scene.

Eye-Level Panoramic Picture

As we created the 3-D videos, we became aware of the challenge of accurately measuring tree cover density in a fashion that represented how individuals see and experience urban trees. Inspired by the work of Nordh and colleagues (2009), we addressed this challenge by creating panoramic pictures taken from the 3-D videos. Using the panoramic pictures, we calculated tree cover density with a high degree of accuracy by identifying the number of pixels associated with tree cover. In contrast to measurements of tree cover calculated from aerial photography, eye-level tree cover density is closer to people's visual experience because it has a similar visual angle and scope. Thus, eye-level measures of tree density may be a better predictor of the impact of trees on people than top-down tree cover density. However, because this is a new way of measuring tree cover density, future studies should replicate this method for various urban spaces.

Implications for Practice

Our findings reinforce the importance of adding trees to community streets. The findings here add to the body of evidence showing that urban forestry can promote the health and well-being of neighborhood residents. Landscape planners and city managers can use these findings to better allocate limited urban forest resources for community streets and other urban spaces.

These findings also suggest that landscape architects, planners, and policy makers should consider using eye-level photography to calculate tree cover density because it is associated with the effect of trees on stress recovery. Eye-level tree cover density is a more accurate measure of how much tree canopy people can see in their communities than top-down tree cover density.

The vast majority of urban foresters use aerial images to assess tree cover density. It is important, therefore, to investigate the extent to which there is a significant association between eye-level tree cover density and tree cover density measured from aerial images. To what extent are these measures correlated? Are there conditions under which they are more or less correlated? Such questions are important because communities across the world are now setting tree density goals based on measures taken from aerial imagery.

Another implication concerns community design. To yield significant stress recovery effects, landscape planners and policy makers should put trees in the places people frequent the most for physical and social activities, such as streets, pathways, community gardens, and front yards. It is also important to consider how much tree canopy people can see through windows or as they sit on their front porches or back patios.

Conclusion

We close by noting the importance of helping people recover from stress by viewing, or being in, nature even within urban environments. The findings here suggest a community street scene with a higher density of street trees would elicit greater stress reduction than that of a similar scene with fewer trees. Although the effect size for the impact of tree density on recovery from stress is small, these findings are important considering the nature treatment video was only 6-min long. It is possible that neighborhood residents who spend longer amounts of time in areas with high tree density will experience much greater stress reduction than presented here. These possibilities need to be explored in future research. The findings here provide a comprehensive dose-response curve for the relationship of varying levels of street tree density on self-reported stress recovery that not only extends the body of knowledge but also provides some guidance for design practitioners and city planners. Given that stress is an important predictor of a wide variety of negative health outcomes, the findings here suggest that we can create healthier communities by providing a healthy urban forest.

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