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# Enhanced functional connectivity properties of human brains in nature scenes

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In this study, we investigated the impact of in-situ nature and urban exposure on human brain activities and their dynamics. We randomly assigned 32 healthy right-handed college students (mean age =20.6 years, SD= 1.6; 16 males) evenly to a 20-minute in-situ sitting exposure to either a nature or an urban-built environment, and measured their EEG signals. Analyses revealed that a brief in-situ nature experience may induce more efficient brain connectivity with enhanced small-world properties and stronger global functional connectivity than a stressful urban-built experience. Exposure to nature may also induce stronger long-term correlated activity across different brain regions with a right lateralization. These findings enhance our understanding of the impact of different in-situ environmental exposures on subsequent brain activity, implying that a nature or nature-like environment may benefit cognitive performance and mental well-being. These results may foster the construction of large-scale cortical network models to mimic cognitive computation in real natural situations.

Cover page

Title:

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# 1 Introduction

Real-world society and the surrounding environment may be critical in shaping cognitive functions and brain performance. Evidence has suggested that social pressure and an intense workload can suppress cognitive performance (Juster et al. 2010; Kuhlmann et al. 2005; Takahashi et al. 2004). More recent studies, however, have demonstrated improvements in working memory and attention shortly after a short-term nature experience (Berman et al. 2008; Lee et al. 2015; Taylor & Kuo 2009). In one example, a brief nature walk, as revealed in a recent empirical study, significantly reduced anxiety-related neural activity in the subgenual prefrontal cortex (Bratman et al. 2015b), enhancing positive cognitive performance and emotion regulation as well (Bratman et al. 2015a). This phenomenon suggests that the natural environment in addition to social pressure may be another key factor influencing human cognitive performance. However, only limited evidence exists of environmental impact on human cognitive activity (Bowler et al. 2010).

Previous studies have suggested that  $1/f$  characteristics in the log-log power spectrum (a unique statistical feature of natural signals widely observed in natural environments but rare in urban-built ones) may be potential key factors in shaping cognitive functions during natural adaptation and evolution. More and more studies have revealed that mammalian brains can perform more efficiently in response to naturalistic signals than artificial ones (Simoncelli & Olshausen 2001). A perfect nature-like signal should contain a high-order statistic of a  $1/f^\beta$ -like power spectrum. For example, a natural sound, which is one-dimensional, is close to a power distribution of  $1/f^1$  while a two-dimensional natural image is close to a distribution of  $1/f^2$  and a three-dimensional natural video is close to  $1/f^3$  (Chen 2012). In-vivo evidence has demonstrated that mammalian sensory systems (Gal & Marom 2013; Yu et al. 2005) can process natural signals more efficiently than artificial ones. This characteristic of cognitive functioning may impact the efficiency of neural networks (He 2011) and eventually define global cognitive performance.

The evidence above, therefore, suggests a new hypothesis: specifically, signal statistics may be one critical factor driving human brains to perform more efficiently in nature settings than more urban-built ones. Hence, in this paper, we examine the following questions: Do nature and constructed artifacts differ significantly in their statistics of visual stimuli? Do human brains respond differently to these different statistics? What are the significant differences in the brain when responding to the two types of environmental signals? Although visual signals are probably among the most important stimuli in the two types of environments, we believe that they only partially capture the differences between the two. To fully capture the holistic environmental experience, multisensory immersion is crucial. Therefore, we adopted in-situ exposure instead of pictorial representation. To minimize the external variables that an in-situ experimental design can present, we intentionally controlled the thermal comfort, including temperature, humidity, wind chill, and other conditions, to ensure that the two treatments occurred within equivalent circumstances.

Indeed, our new hypothesis is supported by a recent analysis of auditory perception. This study found that music sound with a  $1/f$  property, comparing to random noise, induced an enhanced brain connectivity with efficient information flow across brain regions featuring a small-world complex network property (Wu et al. 2013; Wu et al. 2012b). Small-world networks are hierarchical structures with more efficient and well-connected hubs, which are widely found in biological, ecological, social, world-wide web, molecular and neuronal networks (Watts & Strogatz 1998b). The small-world network, because of these hubs, usually entails a large clustering coefficient and short path length, enabling more efficient flow of information than that found in

randomly ordered nonhierarchical networks. In this study, we examined the EEG functional connectivity during in-situ nature and urban experiences, including functional correlation, small-world network statistics, 1/f statistics and their lateralization.

Experiment-observed functional network connectivity could be valuable for constructing large-scale neural network models underlying cognitive computation and cortical information processing (Ampazis et al. 2015; Ding et al. 2013; Gao et al. 2014; Sun 2013). In many existing computational designs, networks are generally studied with the resting state as the default mode, which is not the actual state in which brains execute behavior. Our study of how brain functional connectivity changes, both temporally (e.g., 1/f statistics) and spatially (e.g., small-world statistics and correlation) in response to sensory stimuli, may inspire alternative designs for cognitive computation such as reservoir computing and attractor networks (Gros 2009).

## 2 Methods

In this study, we compared the brain performance of 32 healthy right-handed participants (mean age=20.6, SD=1.6, 16 males) during a 20-minute in-situ sitting exposure to nature and to a constructed environment. We utilized a portable wireless EEG recording device in addition to self-report psychological scales. This study was approved and supervised by the Ethics Committee of Tongji University (no. 2015xy103).

No significant neurotic personality was found among the participants as indicated by scores (mean = -1.58~1.33 on a 7-point Likert scale) from the neuroticism subscale of the NEO Personality Inventory (Costa & McCrae 1992). Participants reported small everyday stresses (mean= 0.29, SD=1.90 on a 7-point Likert scale) and slightly stress-reducing living environments (mean=0.32, SD=1.40 on a 7-point Likert scale). They were generally well rested (sleeping hours=6.90, SD=1.33) with a broad range of work (studying hours = [1.5, 15], mean=8.06, SD=3.25) and entertainment (hours=[1,11], mean=3.25, SD=2.35) schedules, besides moderate exercise (mean hours=0.73, SD=0.49) and exposure to nature (mean hours=0.83, SD=0.68) on a daily basis.

### 2.1. Site Selection

Because this study was designed to examine the extent to which unique statistics of natural signals induce more efficient brain functioning, we used the  $\beta$  values in the 1/f statistics of visual stimuli as criteria for site selection. Research has shown that the  $\beta$  values of nature images are likely to be close to 2 (Szendro et al. 2001; West & Shlesinger 1990) due to an appropriate distribution between low-frequency contours (e.g., shapes of trees, mountains) and high-frequency details (e.g., fractal edges, random texture and lines). This implies a moderate long-term correlation level across image components of all frequency ranges. With increasingly uniform materials (e.g., concrete) and limited high-frequency detail, urban-built scenes may be more likely to reveal a larger  $\beta$ , but we were less confident before verification.

To find a typical nature and urban-built environment, we first examined a large number of photographs. Because of limited confidence in the  $\beta$  estimation for built scenes, we intentionally investigated a larger sample of photographs of urban-built scenes (n=135) than nature scenes (n=80). All of the photos had been captured and reviewed by professional landscape architects and

architects. Both nature and urban photos revealed a normal distribution of  $\beta$  (Fig. 1c and d), with means of 2.30 (SD=.22) and 2.61 (SD=.18), respectively (Fig. 1a). These results were consistent with those from a previous study (Braun et al. 2013) which documented an average  $\beta$  of 2.24 (SD=.19) for nature scenes and 2.53 (SD=.24) for buildings, amidst sample sizes of 200 photos each.

Therefore, we intentionally selected two typical sites with representative  $\beta$  slopes: a wooded campus garden ( $\beta=2.24$ ) for the nature scene and a traffic island under an elevated highway ( $\beta=2.62$ ) for the urban-built scene (Fig. 1b). Specifically, the nature scene consisted of 89% visible green and water along with 4% visible buildings and paved areas from where participants were seated while the urban-built scene consisted of 8% visible green with 56% visible buildings and paved areas (Fig. 2). To control for external variables such as thermal comfort levels, all experiments were conducted in May and June in a comfortable temperature of 22 degrees centigrade (difference within  $\pm 5$ ), 81 percent humidity (difference within  $\pm 13$ ), an acoustic level of 72 db (difference within  $\pm 12$ ), and a wind speed of 0.8 m/s or slower.

## 2.1. Procedure and Data Validity Control

The experiment was taken via a structured procedure (Fig. 3). After first signing a written consent form containing a written explanation of the experimental procedure and risks, participants completed a two-page pretest questionnaire. Portable EEG electrodes were positioned onto participants' scalps, and they were then asked to sit facing a wall to temporarily exclude visual information. Participants were instructed to alternate keeping their eyes open and closed in four one-minute cycles. After this pre-experimental phase, participants were told to turn and face the environment for 20 minutes<sup>1</sup>. Participants were asked to sit either in a built environment (i.e., a traffic island under an elevated highway), or in a natural environment (i.e., a heavily wooded campus garden) facing a designated view. After viewing the environment, participants completed a posttest questionnaire and a short interview. To prevent their minds from wandering or becoming drowsy, participants were told to count from 1 to 1000 soundlessly at a speed which was slow enough not to interrupt the environmental experience.

We specifically adopted eye-opened and eye-closed pretests in the beginning of the experiment to verify the reliability/stability of electrode recording across the 20 minutes of environment exposure. We examined the power distribution and 1/f statistics of two electrodes at the primary visual cortex (O1 and O2) during the two pretests. The results revealed a clear 1/f statistic in both the nature and built environments (Fig. 3b~c). At both sites, there was also a clear bump at the top of the 1/f slope near  $\log f=1$  (the location of the alpha range) during the eye-closed session, while the bump dropped towards the slope during the eye-open session. This bump-dropping effect during the eye-open session is called alpha-blocking (Könönen & Partanen 1993). The successful capture of 1/f statistics (arrhythmic firing) and alpha-blocking (rhythmic oscillation) as expected supports the validity of the data.

<sup>1</sup> EEG of the entire 20-minute exposure was measured for the latter 16 participants (8 nature) while only the latter half (10 minutes) of the exposure was measured for the first 16 participants (8 nature). Paired t-test revealed no significant differences between the first half (10 minutes) and the latter half (10 minutes) of exposure for the 16 participants whose EEG was recorded for the entire 20 minutes in terms of EEG correlation and  $\beta$  exponent, except for two individuals in the built environment groups (see supporting materials). Therefore, the full recording length from both groups (10 minutes for first half and 20 minutes for the latter half) was used for analyses.



## 2.2. Measures

Participant affective status was measured both before and after the environmental exposure using the Profile of Mood State questionnaire (Curran et al. 1995). In this questionnaire, participants were asked to rate the extent to which 40 descriptive words captured their affective status on a 7-point Likert scale.

An Emotiv wireless headset (Dekihara & Iwaki 2014) and accompanying software was used to measure EEG. The headset consists of 14 sensors positioned on the wearer's scalp according to the international 10–20 system: antero-frontal (AF3, AF4, F3, F4, F7, F8), frontocentral (FC5, FC6), occipital (O1, O2), parietal (P7, P8) and temporal sites (T7, T8). Brain waves are measured in terms of amplitude (10–100 microvolts) and frequency (1–70 Hz). EEG data were analyzed via Matlab and EEGLab. Data were first filtered (<0.5Hz or >50 hz) using EEGLab and adjusted for artifacts using Adjust 1.1 (Mognon et al. 2011).

The signal was first analyzed via Fast Fourier Transformation and then categorized into five frequency bands: delta (1–4 Hz), theta (5–8 Hz), alpha (9–12 Hz), beta (13–25 Hz), and gamma (26–45 Hz). Total mean power by frequency bands and brain connectivity were calculated.

### Correlations

Correlations between signals at different electrodes were calculated using the following equation:

$$r(x) = C_{AB}(x) / (C_{AA}C_{BB}) \quad (1)$$

where the cross-covariance between signals A and B was noted as  $C_{AB}$  while the auto-covariances of signals A and B were noted as  $C_{AA}$  and  $C_{BB}$ , respectively (Guevara & Corsi-Cabrera 1996).

### Small-World Network Statistics (Watts & Strogatz 1998b; Wu et al. 2013)

We used a small-world characteristic value  $C_{\text{mean}} / L_{\text{mean}}$  to measure the small-world network propriety, where  $L_{\text{mean}}$  is the averaged shortest path length and  $C_{\text{mean}}$  is the clustering coefficient. A higher small-world characteristic value  $C_{\text{mean}} / L_{\text{mean}}$  indicates a higher clustering effect at smaller path lengths, which is therefore indicative of more distinct small-world characteristics. The clustering coefficient of an electrode  $v_i$  was calculated as

$$C_{v_i} = \begin{cases} 0 & k \leq 2 \\ \frac{2n}{k(k-1)} & k > 2 \end{cases} \quad (2)$$

where  $k$  denotes the number of electrodes of an EEG correlation with the electrode  $v_i$  higher than a given threshold, and  $n$  denotes the number of paths with a correlation higher than the threshold between the  $k$  electrodes that it is connected to (where  $n$  equals  $C_k^2$  in a saturated scenario). The averaged clustering coefficient for an individual is then calculated as

$$C_{\text{mean}} = \frac{1}{14} \sum_{i=1}^{14} C_{v_i} \quad (3)$$

The shortest path length was calculated from the shortest of all total paths from  $v_i$  to  $v_j$  for a pair of electrodes  $v_i$  and  $v_j$ , using the Floyd algorithm. The path length between two immediate neighbors was coded as 0 (to itself), 1 (beyond threshold) or 13 (below threshold). For each individual,



$$L_{mean} = \frac{1}{C_{14}^2} \sum_{\substack{i=1, j=1 \\ i < j}}^{14} L_{v_i, v_j} \quad (4)$$

where  $L_{v_i, v_j}$  denotes the shortest path length between a pair of electrodes  $v_i$  and  $v_j$ .

### 1/f Statistics

The 1/f statistics were calculated as the regression slope  $\beta$  (absolute value) of the log power over the log frequency in a 1/f<sup>β</sup> power spectrum. The  $\beta$  values were first calculated at each electrode for each individual and then linearly combined as electrode and individual global means. Lateralization was calculated as log(R)-log(L), where R and L represent the right and left symmetrical pairs (i.e., AF4/AF3, F8/F7, F4/F3, FC6/FC5, T8/T7, O2/O1), respectively.

### Statistical Test

As we were primarily interested in documenting how brain regions responded to environmental stimuli, all differences were tested against electrode variance using T test paired by electrodes, with an exception of small-world network property which was tested against individual variances using independent T test.

## 3 Results

### 3.1. Impact on Affect and EEG Power

To investigate the impact of environmental exposures on affect, we linearly combined the constructs on a 7-point Likert PMOS psychological scale reported by participants. All participants sitting in front of nature, after a 20-minute exposure, reported a more positive affective status than those sitting in front of a built environment. Specifically, nature-exposed participants reported less fatigue (nature=-2.38, SD=4.65; built=1.69, SD= 4.73;  $p=.020$ ), as well as better-maintained vigor (nature=-.50, SD=4.65; built=-4.08, SD=3.18;  $p=.04$ ) and less negative mood disturbance (nature=-.394, SD=11.29; built =9.64, SD=15.07;  $p=.007$ ).

To investigate the impact of environmental exposures on EEG power, we performed a two-way ANCOVA on EEG power in five frequency bands (delta, theta, alpha, beta and gamma) in two conditions (nature and built environment exposures) with their eye-open pretest baselines controlled. ANCOVA confirmed a significant overall power difference between nature and built environment ( $F(1,129)=4.175$   $p=.043$ ), with a higher power found during nature exposure in all frequency bands confirmed by T-test paired by channels (all  $p<.001$ , compared at a Bonferroni correction of  $.05/5=.01$ ).

### 3.2. Impact on Functional Connectivity and Signal Correlation

We analyzed the averaged correlations of EEG power at different frequency bands to understand the functional connectivity (Fig.4). A channel-wise two-way ANCOVA was performed on EEG power correlation in five frequency bands (delta, theta, alpha, beta and gamma) and in two conditions (nature and built environment exposures) with their eye-open pretest baselines controlled. We observed a significant higher overall power correlation during nature exposure

compared at that during built environment exposure ( $F(1,129)=85.09$ ,  $p<.001$ ), with a higher power found during nature exposure observed in delta ( $p=.008<.01$ , compared at a Bonferroni correction of  $.05/5=.01$ ), theta, alpha and beta (all  $p<.001<.01$ ).

We then analyzed the averaged correlations of EEG power to analyze the difference across electrodes. A participant-wise two-way ANOVA was performed on mean EEG power correlation in 14 electrodes and in two conditions (nature and built environment exposures) with their eye-open pretest baselines controlled. Again, we observed a significant a significant higher overall power correlation during nature exposure compared at that during built environment exposure ( $F(1,419)=15.32$ ,  $p<.001$ ), but no significant difference at individual electrode using independent T test after Bonferroni correction.

### 3.4. Impact on Small-World Network

At the beginning, we calculated the average shortest path length  $L_{mean}$  and network clustering coefficients  $C_{mean}$  to quantify the information flow efficiency within the network. We observed that  $L_{mean}$  was slightly smaller in the nature scene condition than in the urban environment (Fig. 5a), although there was no significant difference observed across all threshold values. The clustering coefficients were significantly higher in the nature scene condition than the urban condition for the medial threshold values (Fig. 5b), indicating a better small-world property. To see this clearly, we defined a new measure  $C_{mean}/L_{mean}$  to directly quantify the small-world characteristic to evaluate the impact of environmental exposure on brain functional network connectivity. We observed higher values for  $C_{mean}/L_{mean}$  for almost all thresholds (Fig. 5c) for the nature scene (the t-test against participant variances indicated significance at .50 with  $p=.041$ , .60 with  $p=.046$  and .095 with  $p=.044$ , respectively). Hence, participants sitting in the nature scene may have had more efficient information communication because of a better small-world network property.



### 3.5. Impact on the temporal long-term correlation (1/f characteristic) of EEG

To investigate the 1/f statistics during the two environmental exposures, we first investigated the global  $\beta$  value averaged across the  $\beta$  values of all electrodes. We found, as expected, a significant difference during the viewing of the two scenes ( $p=.033$ , t-test paired by electrode, Fig. 6a). To further investigate the spatial variation of 1/f statistics, six brain regions were studied: the left (AF3, F7 and F3) and right antero-frontal (AF4, F8 and F4), left (FC5 and T7) and right temporal/frontocentral (FC6 and T8), left (P7 and O1) and the right parietal/occipital (P8 and O2). A trend towards larger  $\beta$  slopes in these brain regions was observed during the nature experience (Fig. 6b). After noticing a possible lateralization effect of  $\beta$  during the above brain region analysis, we compared the lateralization of  $\beta$  between nature and built environment exposure. The two environments revealed distinct lateralization in  $\beta$  values. Specifically, a right lateralization (a larger  $\beta$  slope in the right) was found at F8/F7 ( $p=.030$ , t-test against participant variance), FC6/FC5 ( $p=.005$ ) and T8/T7 ( $p<.001$ ) in the nature experience while a right lateralization at T8/T7 ( $p=.002$ ) and P8/P7 ( $p<.001$ ) was instead found for the built environment (Fig. 6c).

# 4 Discussion

While studies have emphasized that the social pressures of urban life can induce cognitive decline and discomfort (Lederbogen et al. 2011), our study revealed that the distinct statistical properties of the artificial built environment relative to those from the natural scenes also induce different macro statistical properties of brain EEG signals, which may therefore lead to cognitive decline and discomfort. Growing experimental and theoretical evidence supports the notion that human and animal visual systems are adapted to represent natural scenes efficiently (Simoncelli & Olshausen 2001). The statistics of natural images are typically characterized by the scale-invariant power spectra, with the slope of the frequency-power relationship in a log-log plot close to 2 (the so called  $1/f^2$  statistics) (Ruderman 1997; Ruderman & Bialek 1994). The slope of 2 suggests the presence of long-term correlations among picture pixels in different scales. Because brain vision systems have evolved in the natural world, it has been strongly suggested (Olshausen & Field 1996; Simoncelli & Olshausen 2001) that early visual pathways were adapted to de-correlate the correlational structure of the input signals efficiently and then pool all the encoded information together in the higher level cortex to formulate internal pictures of the outward natural world. Hence, brain sensory systems may function more efficiently in response to the natural scene's characteristics and consume less energy in their visual processing of natural signals (Laughlin 2001; Olshausen & Field 1997; Simoncelli & Olshausen 2001). As stated in our previous study of primates (Yu et al. 2005), the visual function of cortical neurons may be designed to tune to  $1/f$  characteristics for efficient coding, which induce a preference in the visual system for natural signals in the natural environment. In addition, a recent study (Torralba & Oliva 2003) reported that cardinal (horizontal and vertical) orientations are more prevalent in sample image statistics of man-made artifacts (e.g., urban buildings, streets, highway infrastructures) than in images of natural scenes. In addition, there are more low frequency components and less high frequency components in built artificial views, resulting in a larger slope ( $\geq 2.5$ ) in the power spectra of urban images (Braun et al. 2013; Torralba & Oliva 2003). This raises a nontrivial issue. That is, after prolonged exposure to built artifacts with signal statistics distinct from nature, could human neural responses differ in terms of statistical properties and therefore become overstressed and uncomfortable (Penacchio & Wilkins 2015)? Actually, recent studies have documented a significant drop in both self-reported rumination and neural activity in the subgenual prefrontal cortex of healthy participants after a 90-min walk in a natural environment, while no such effect was observed for an urban walk (Bratman et al. 2015b).

Our study here examined the above issues and observed several new statistical properties of brain EEG responses for humans set in nature or urban environments. First of all, as expected, analysis of the questionnaire forms reported that all the participants reported more pleasant feelings and less stress in nature than in the urban-built environment. Second, when observers were sitting within nature, their brain EEG activities were more strongly correlated (almost among all frequency bands) across the whole brain globally than those sitting in an urban environment. This suggests that different cortical regions may be in more organized functional states. This idea has been supported by recent behavior studies which revealed that performance on working memory tasks improved shortly after a nature experience (Berman et al. 2008; Bratman et al. 2015a; Taylor & Kuo 2009). The lower global functional EEG connectivity observed during the urban experience may imply that our neural network may be less efficient at perceiving and reconstructing urban environment and built artifacts. However, further studies are needed to verify this tentative hypothesis.

Furthermore, we also calculated the small-world property of all the brain EEG recording sites (Smit et al. 2008; Watts & Strogatz 1998a). Network measures were calculated as a function of a certain Pearson correlation threshold value. There was a larger small-world network characteristic value  $C_{\text{mean}}/L_{\text{mean}}$  in the nature than in the urban condition, with a significantly larger clustering coefficient  $C_{\text{mean}}$  at thresholds of .50 ( $p=.041$ ), .60 ( $p=.046$ ) and .95( $p=.044$ ). The enhanced small-world network in nature exposure suggests a more optimized configuration and a higher efficiency of information transfer across the brain regions than that in the urban-built environment. This enhanced small-world property has also been observed in the context of music perception (Wu et al. 2012a) when compared to noise listening.

In addition, we have also studied the power spectrum properties of EEG signals and observed that they demonstrated a reversed power law phenomenon, called  $1/f^\beta$  statistics in the frequency domain, indicating a power law distribution of frequencies. The  $1/f^\beta$  statistics suggest long-term correlations in the time domain. A large  $\beta$  value means that any two time events in the EEG signal have a relatively large correlation time constant. A  $1/f^\beta$  power spectrum, with power tending to fall off with increasing frequency, indicates no particularly dominating periodic oscillatory dynamic. Hence, a pure  $1/f^\beta$  phenomenon is indicative of arrhythmic activity. Because EEG signals are also well-known to be characterized by the different oscillatory bands, e.g.,  $\delta$  (0-3Hz),  $\theta$  (4-7Hz),  $\alpha$  (8-12Hz) and  $\beta$  (13-30Hz), frequency bands that are correlated with some special brain behavior state, the above observations suggest that brain activities are a combination of oscillatory activity and arrhythmic activity. For decades, research has concentrated on the former and discarded the latter as pure noise. Not until recently did evidence reveal that the latter was more than just noise and may be intimately related to brain functioning(Ray & Maunsell 2011). In this study, we observed a larger  $\beta$  value for brain EEG in the natural scene than was observed in the urban environment. The larger power-law exponent  $\beta$  suggests a higher time-lagged autocorrelation, indicating that the past dynamics of the system have a stronger influence on its future dynamics, i.e., the system has more long-range memory. A reduced power-law exponent might indicate enhanced working task behavior, as observed in an ECoG study during a visual detection task of unpredictable stimuli(He et al. 2010). Therefore, our observation here of a larger  $\beta$  value for brain EEG in the natural scene may suggest more relaxed and associated brain states than what exists in urban environments. However, identifying the best range of  $\beta$  values for the brain in the best performance or most pleasant state requires a better designed task in the future.

The general observation that brain signals contain long-term correlation and oscillatory components might reflect interactions between bottom-up information process and top-down cognitive feedback. This requires further investigation to deepen our understanding of cognitive computation processes within the brain. It will be interesting to construct large-scale cortical circuit models to investigate the biophysical mechanism of the  $1/f$  response and the oscillation characteristics as revealed in this study. These brain response features, potentially important to brain functioning (He 2014; Watts & Strogatz 1998b), have barely been considered in current cognitive computational models. Moreover, the preference of brain sensory system for the  $1/f$  characteristic may also require further investigation of cortical computational modeling to reveal the biophysical mechanism underlying cortically efficient coding. The experimental investigation of the relationship between environmental statistics and cognitive processing could be valuable for number of reasons. First, it may deepen our understanding of the functional properties of brain sensory systems. Second, it may foster the derivation of new cortical computation models based on environmental statistics for efficient coding. It might also be helpful in the design of new forms of stochastic experimental protocols and stimuli for probing different brain sensory systems.

Certainly, the results here can also lead to fundamental improvements in the design of naturalistic urban architecture that strengthens brain cognitive performance and computation.

In sum, while many studies have emphasized the impact of urban social pressure (e.g., unemployment, poverty) as being one of the critical stressors on human health and wellbeing (Seresinhe et al. 2015; Tost et al. 2015), a brief walk or sitting in a natural environment, e.g., pure natural woods, could benefit brain cognitive performance and alleviate the negative stressors. Our studies suggest that a nature environment, as characterized by the long-term correlation statistics in their visual signals, can evoke different brain oscillatory activity and arrhythmic activity, which may help place brain functioning in a more pleasant and less-stressful state. In other words, brains generate more memory-like effects of auto-correlated electrical signals when we are watching nature than when we are watching a busy built environment. This might be an indication of better memory formation in the natural environment than in the urban environment. Moreover, it may be possible that this "redundant" autocorrelation, which is seen in many natural phenomena as well as neuronal signals, could be important to our resilience and mental wellbeing. This idea requires further careful investigation.

## 4 Summary

In last decades, there are increased experimental evidences reported that animal sensory neurons process natural signals more efficiently than artificial signals (Lewen et al. 2001; Rieke et al. 1995). Computational studies revealed that the structure and function of sensory neurons and network may be designed to efficient coding to signals in natural environment due to long-term adaptation and natural evolution. Our study designed in an early stage to examine whether the human brain function more efficiently in a natural environment than in urban environment. The answer and underlying mechanism related to this issue may be critical to understanding the operating principle of human brains.

Previous experiments have revealed that a short walk in purely natural wooded area may greatly refresh the brain's cognitive performance and alleviate negative stressors. Our study revealed that in addition to the social pressures found in urban environments, the distinct statistical properties of the built artifacts may also shape the human brain response properties differently, and thus, further stress human brains. Additional investigations are needed to more precisely examine the performance differences observed between these two types of environments.

This study revealed the presence of a more efficient brain network during a nature experience than during an urban one. Specifically, stronger global functional connectivity was observed in nature, as well as a more enhanced small world property with a higher small-world characteristic value ( $C_{\text{mean}}/L_{\text{mean}}$ ) and higher mean clustering coefficients ( $C_{\text{mean}}$ ) at .50, .60 and .95. The more efficient brain network in nature may help explain the better affective states reported in this study and the potential cognitive improvements exhibited shortly after a nature experience as observed elsewhere in the research literature (Berman et al. 2008; Bratman et al. 2015a; Taylor & Kuo 2009).

This study also documented some relevant changes to long-term correlation characteristics of human EEG signals during in-situ environmental exposures to nature and to a built environment. We found a larger  $\beta$  exponent in the  $1/f^\beta$  frequency spectrum during the nature experience, as well as a larger  $\beta$  in the right hemisphere during the exposures to nature and to the built environments with distinct differences. This may be among the earliest studies of changes in the  $1/f$  power spectrum exponent  $\beta$  of human EEG signals as a function of different environmental experiences.



A larger sample size and repeated experiments are needed to further investigate the key properties intrinsic within the nature-related that impact the resulting EEG signal statistics. Greater understanding of the functional connectivity characteristics observed in this study in response to different environmental stimuli will be beneficial in constructing better cognitive computational models.

## References

- Ampazis N, Perantonis SJ, and Drivaliaris D. 2015. Improved Jacobian Eigen-Analysis Scheme for Accelerating Learning in Feedforward Neural Networks. *Cognitive Computation* 7:86-102. 10.1007/s12559-014-9263-2
- Berman MG, Jonides J, and Kaplan S. 2008. The cognitive benefits of interacting with nature. *Psychological Science* 19:1207-1212.
- Bowler DE, Buyung-Ali LM, Knight TM, and Pullin AS. 2010. A systematic review of evidence for the added benefits to health of exposure to natural environments. *BMC Public Health* 10:456.
- Bratman GN, Daily GC, Levy BJ, and Gross JJ. 2015a. The benefits of nature experience: Improved affect and cognition. *Landscape and Urban Planning* 138:41-50. <http://dx.doi.org/10.1016/j.landurbplan.2015.02.005>
- Bratman GN, Hamilton JP, Hahn KS, Daily GC, and Gross JJ. 2015b. Nature experience reduces rumination and subgenual prefrontal cortex activation. *Proceedings of the National Academy of Sciences*:201510459.
- Braun J, Amirshahi SA, Denzler J, and Redies C. 2013. Statistical image properties of print advertisements, visual artworks and images of architecture. *Front Psychol* 4:808. 10.3389/fpsyg.2013.00808
- Chen Y. 2012. Zipf's law, 1/f noise, and fractal hierarchy. *Chaos, Solitons & Fractals* 45:63–73.
- Costa PT, and McCrae RR. 1992. Normal personality assessment in clinical practice: The NEO Personality Inventory. *Psychological Assessment* 4:5.
- Curran SL, Andrykowski MA, and Studts JL. 1995. Short Form of the Profile of Mood States (POMS-SF): Psychometric information. *Psychological Assessment* 7:80.
- Dekihara H, and Iwaki T. 2014. Development of human computer interface based on eye movement using Emotiv EEG headset. *International Journal of Psychophysiology* 2:188.
- Ding Y, Wang T, and Fu X. 2013. Using Neural Networks and Self-Organizing Maps for Image Connecting. *Cognitive Computation* 5:13-18. 10.1007/s12559-012-9161-4
- Gal A, and Marom S. 2013. Entrainment of the intrinsic dynamics of single isolated neurons by natural-like input. *Journal of Neuroscience* 33:7912-7918.
- Gao X, Huang T, Wang Z, and Xiao M. 2014. Exploiting a Modified Gray Model in Back Propagation Neural Networks for Enhanced Forecasting. *Cognitive Computation* 6:331-337. 10.1007/s12559-014-9247-2
- Gros C. 2009. Cognitive computation with autonomously active neural networks: an emerging field. *Cognitive Computation* 1:77-90.
- Guevara MA, and Corsi-Cabrera M. 1996. EEG coherence or EEG correlation? *International Journal of Psychophysiology* 23:145-153.
- He BJ. 2011. Scale-free properties of the functional magnetic resonance imaging signal during rest and task. *Journal of Neuroscience* 31:13786-13795.

- He BJ. 2014. Scale-free brain activity: past, present, and future. *Trends in cognitive sciences* 18:480-487.
- He BJ, Zempel JM, Snyder AZ, and Raichle ME. 2010. The temporal structures and functional significance of scale-free brain activity. *Neuron* 66:353-369.
- Juster R-P, McEwen BS, and Lupien SJ. 2010. Allostatic load biomarkers of chronic stress and impact on health and cognition. *Neuroscience & Biobehavioral Reviews* 35:2-16. <http://dx.doi.org/10.1016/j.neubiorev.2009.10.002>
- Könönen M, and Partanen JV. 1993. Blocking of EEG alpha activity during visual performance in healthy adults. A quantitative study. *Electroencephalography & Clinical Neurophysiology* 87:164-166.
- Kuhlmann S, Piel M, and Wolf OT. 2005. Impaired memory retrieval after psychosocial stress in healthy young men. *J Neurosci* 25:2977-2982. 10.1523/JNEUROSCI.5139-04.2005
- Laughlin SB. 2001. Efficiency and complexity in neural coding. *Novartis Found Symp* 239:177-187; discussion 187-192, 234-140.
- Lederbogen F, Kirsch P, Haddad L, Streit F, Tost H, Schuch P, Wust S, Pruessner JC, Rietschel M, Deuschle M, and Meyer-Lindenberg A. 2011. City living and urban upbringing affect neural social stress processing in humans. *Nature* 474:498-501. 10.1038/nature10190
- Lee KE, Williams KJH, Sargent LD, Williams NSG, and Johnson KA. 2015. 40-second green roof views sustain attention: The role of micro-breaks in attention restoration. *Journal of environmental psychology* 42:182-189. 10.1016/j.jenvp.2015.04.003
- Lewen GD, Bialek W, and de Ruyter van Steveninck RR. 2001. Neural coding of naturalistic motion stimuli. *Network* 12:317-329.
- Mognon A, Jovicich J, Bruzzone L, and Buiatti M. 2011. ADJUST: An automatic EEG artifact detector based on the joint use of spatial and temporal features. *Psychophysiology* 48:229-240.
- Olshausen BA, and Field DJ. 1996. Emergence of simple-cell receptive field properties by learning a sparse code for natural images. *Nature* 381:607-609. 10.1038/381607a0
- Olshausen BA, and Field DJ. 1997. Sparse coding with an overcomplete basis set: a strategy employed by V1? *Vision Res* 37:3311-3325.
- Penacchio O, and Wilkins AJ. 2015. Visual discomfort and the spatial distribution of Fourier energy. *Vision Res* 108:1-7. 10.1016/j.visres.2014.12.013
- Ray S, and Maunsell JH. 2011. Different Origins of Gamma Rhythm and High-Gamma Activity in Macaque Visual Cortex. *Plos Biology* 9:141-150.
- Rieke F, Bodnar DA, and Bialek W. 1995. Naturalistic stimuli increase the rate and efficiency of information transmission by primary auditory afferents. *Proc Biol Sci* 262:259-265. 10.1098/rspb.1995.0204
- Ruderman DL. 1997. Origins of scaling in natural images. *Vision Res* 37:3385-3398.
- Ruderman DL, and Bialek W. 1994. Statistics of natural images: Scaling in the woods. *Phys Rev Lett* 73:814-817.
- Seresinhe CI, Preis T, and Moat HS. 2015. Quantifying the Impact of Scenic Environments on Health. *Scientific Reports* 5:16899. 10.1038/srep16899
- Simoncelli EP, and Olshausen BA. 2001. Natural image statistics and neural representation. *Annu Rev Neurosci* 24:1193-1216. 10.1146/annurev.neuro.24.1.1193
- Smit DJ, Stam CJ, Posthuma D, Boomsma DI, and de Geus EJ. 2008. Heritability of "small-world" networks in the brain: a graph theoretical analysis of resting-state EEG functional connectivity. *Hum Brain Mapp* 29:1368-1378. 10.1002/hbm.20468

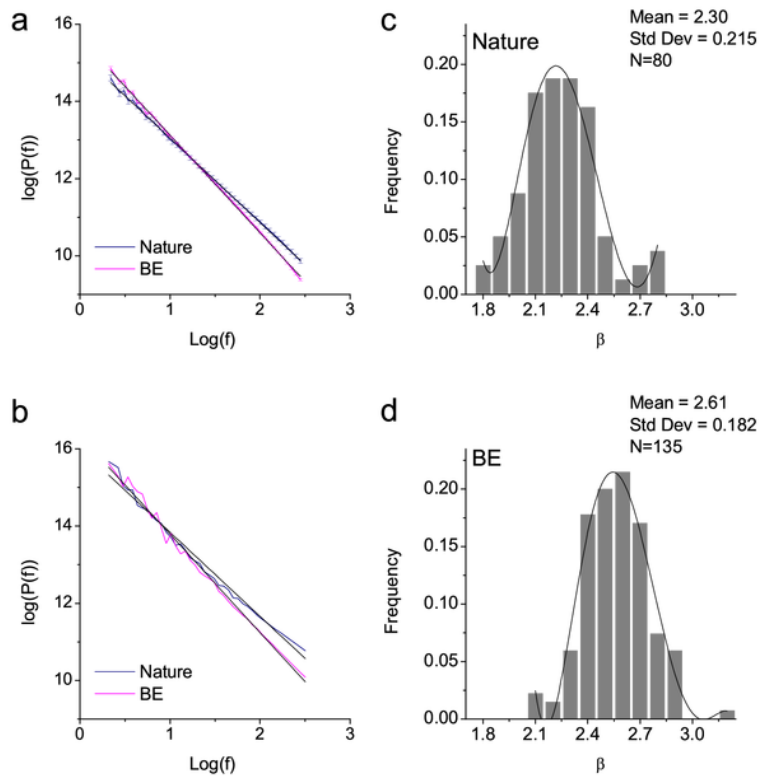


- 505 Sun R. 2013. Moral Judgment, Human Motivation, and Neural Networks. *Cognitive Computation*
- 506 5:566-579. 10.1007/s12559-012-9181-0
- 507 Szendro P, Vincze G, and Szasz A. 2001. Pink-noise behaviour of biosystems. *European*
- 508 *Biophysics Journal* 30:227-231.
- 509 Takahashi T, Ikeda K, Ishikawa M, Tsukasaki T, Nakama D, Tanida S, and Kameda T. 2004.
- 510 Social stress-induced cortisol elevation acutely impairs social memory in humans.
- 511 *Neuroscience letters* 363:125-130.
- 512 Taylor AF, and Kuo FE. 2009. Children with attention deficits concentrate better after walk in the
- 513 park. *Journal of attention disorders* 12:402-409.
- 514 Torralba A, and Oliva Ah. 2003. Statistics of natural image categories. *Network* 14:391-412.
- 515 Tost H, Champagne FA, and Meyer-Lindenberg A. 2015. Environmental influence in the brain,
- 516 human welfare and mental health. *Nature Neuroscience* 18:1421-1431. 10.1038/nn.4108
- 517 Watts DJ, and Strogatz SH. 1998a. Collective dynamics of 'small-world' networks. *Nature*
- 518 393:440-442. 10.1038/30918
- 519 Watts DJ, and Strogatz SH. 1998b. Collective dynamics of 'small-world' networks. *Nature*
- 520 393:440-442.
- 521 West BJ, and Shlesinger M. 1990. The Noise in Natural Phenomena. *American Scientist* 78:40-45.
- 522 10.2307/29773862
- 523 Wu J, Zhang J, Ding X, Li R, and Zhou C. 2013. The effects of music on brain functional networks:
- 524 a network analysis. *Neuroscience* 250:49-59.
- 525 Wu J, Zhang J, Liu C, Liu D, Ding X, and Zhou C. 2012a. Graph theoretical analysis of EEG
- 526 functional connectivity during music perception. *Brain Res* 1483:71-81.
- 527 10.1016/j.brainres.2012.09.014
- 528 Wu J, Zhang J, Liu C, Liu D, Ding X, and Zhou C. 2012b. Graph theoretical analysis of EEG
- 529 functional connectivity during music perception. *Brain Research* 1483:71-81.
- 530 Yu Y, Romero R, and Lee TS. 2005. Preference of sensory neural coding for 1/f signals. *Physical*
- 531 *review letters* 94:108103.
- 532
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# 1

The 1/f statistics of visual stimuli in the nature and urban-built scenes.

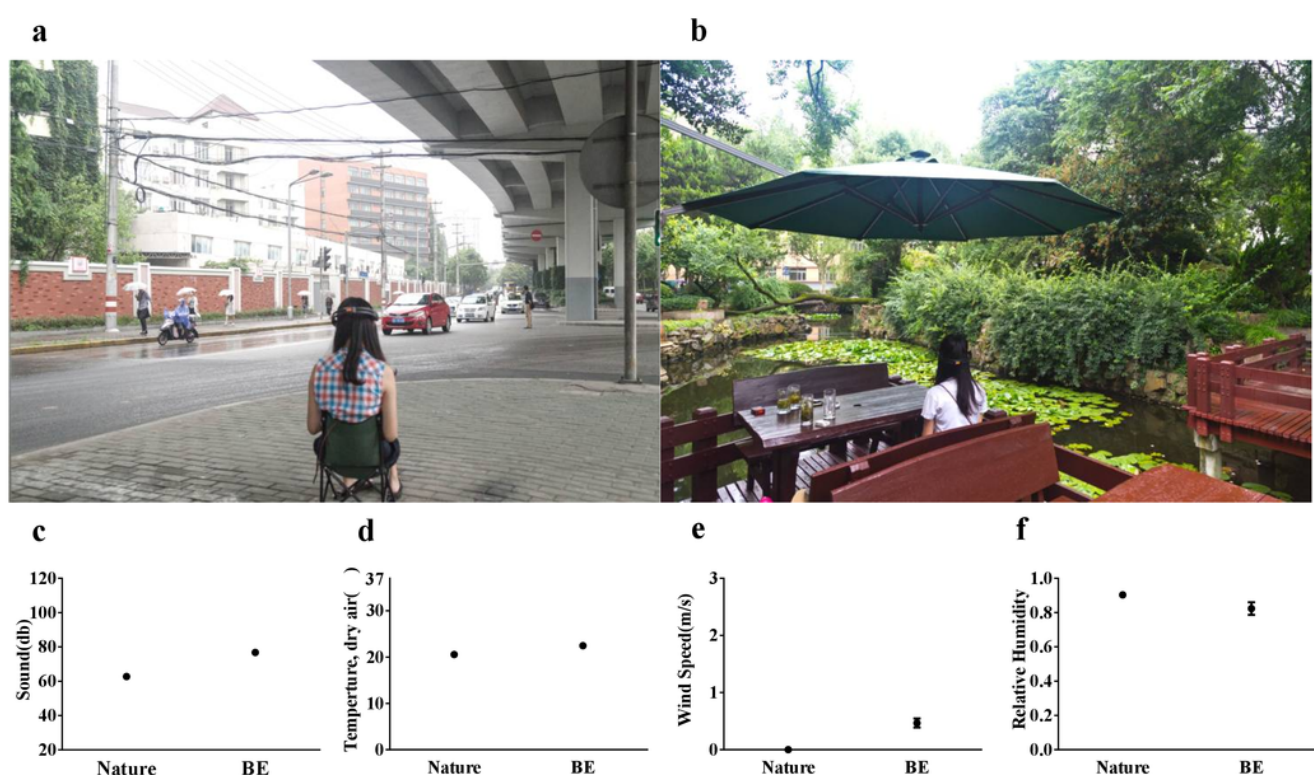
Eighty nature images and 135 urban-built environment (BE) images were analyzed, yielding distinct  $\beta$  slopes (*a*) in the nature (mean=2.30, SD=.22) and urban-built environment (mean=2.61, SD=.18,  $p<.001$ ). The  $\beta$  distributions of the analyzed nature (*c*) and urban-built (*d*) environments are shown. We then selected two sites (*b*) with visual 1/f statistics representative of a nature ( $\beta=2.24$ ) and urban-built environment ( $\beta=2.62$ ). Error bars denote SEM.



# 2

Environmental conditions of the experiment.

A shaded traffic island as a built environment site (a) and a campus garden as a nature site (b). Acoustic conditions (c), temperatures (d), wind speed (e) and relative humidity (f) were intentionally documented and controlled. Error bars denote SEM.

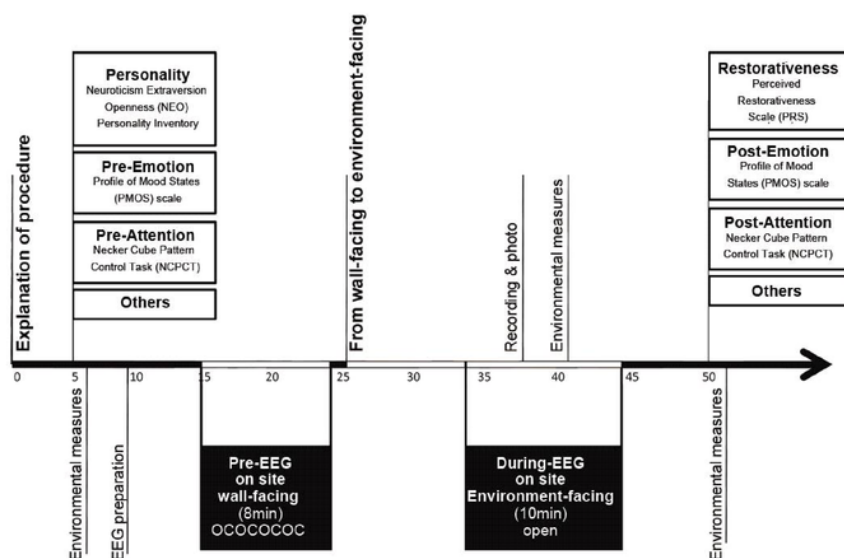


# 3

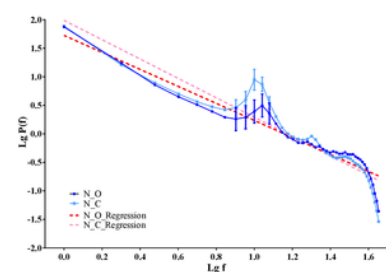
## Experiment procedure and data validity.

Experiment procedure (a) was illustrated. The EEG log-transformed power distribution, as observed at the occipital lobe (O1 and O2) during the pre-test eye-open sessions and compared to the eye-closed session in both the nature (b) and built (c) environment sites, revealed a clear 1/f statistic and alpha-blocking effect. Error bars denote SEM.

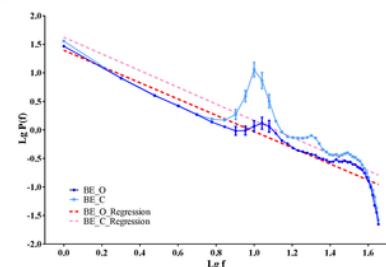
a



b



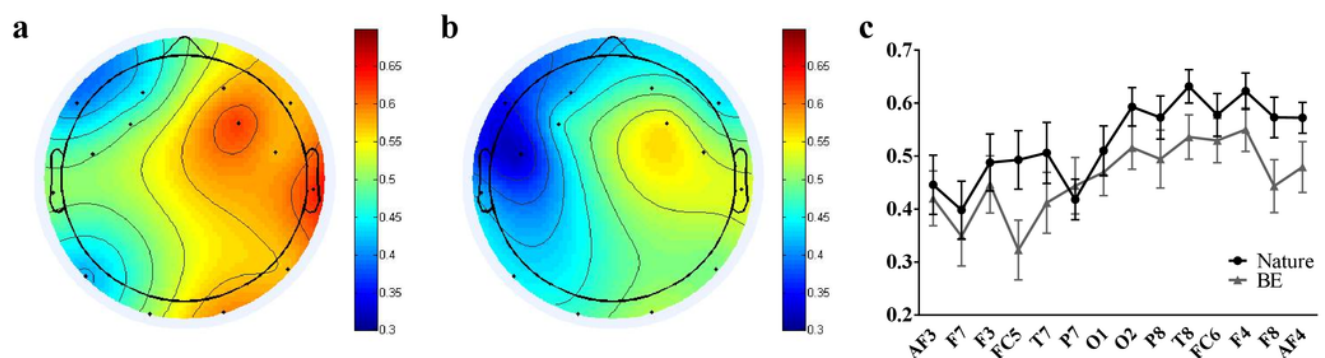
c



# 4

EEG functional connectivity.

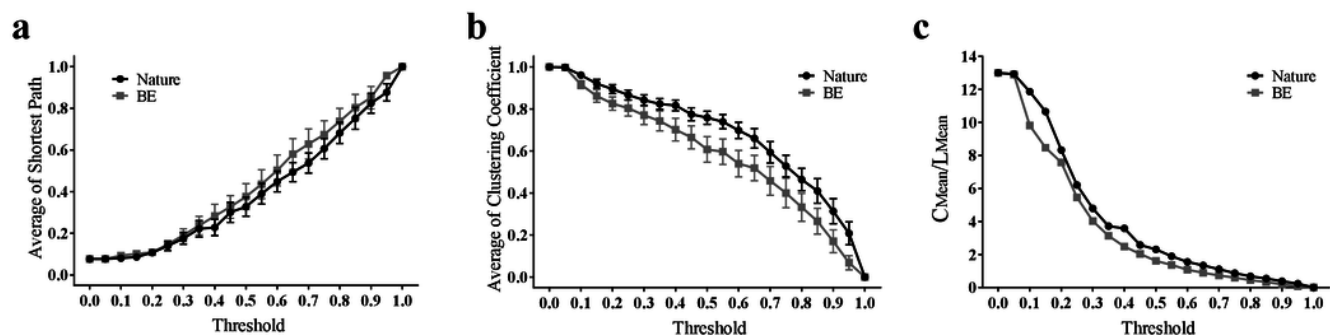
A higher global EEG correlation ( $p < .001$ , paired t-test by electrode) was found during nature experience (a) relative to the urban experience (b) while no significant difference was found in the eye-open baselines ( $p = .314$ , paired t-test by electrode). Average correlation coefficients ranged from 0.3 (blue) to 0.7 (red) at the 14 electrodes (c). Error bars denote SEM.



# 5

EEG small-world network statistics.

The average shortest path length  $h$  ( $L_{mean}$ ) and average clustering coefficients ( $C_{mean}$ ) in the nature and built environment experience. Although  $L_{mean}$  was comparable between the two exposures (a), a higher  $C_{mean}$  (b) was observed during the nature experience at a threshold of .50 ( $p=.041$ , t-test against participant variance), .60 ( $p=.046$ ) and .95 ( $p=.044$ ). A higher  $C_{mean}/L_{mean}$  coefficient was consistently observed at virtually all thresholds (c). Error bars denote SEM.





# 6

The 1/f statistics of EEG.

EEG signals during the nature experience revealed a larger global  $\beta$  exponent than in the built environment (*a*,  $p=.033$ , t-test paired by electrode). The  $\beta$  values in the sub-brain regions are illustrated (*b*). A larger  $\beta$  in the right hemisphere (calculated by  $\beta$  lateralization, i.e.,  $\beta_{\text{right}} - \beta_{\text{left}}$ ) was found during the nature experience at F8/F7 ( $p=.030$ , t-test against participant variance), FC6/FC5 ( $p=.005$ ) and T8/T7 ( $p<.001$ ) while the built environment experience revealed a different right lateralization at T8/T7 ( $p=.002$ ) and P8/P7 ( $p<.001$ ). Error bars denote SEM.

