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Spend time outdoors for your brain – an in-depth longitudinal MRI study

Simone Kühn^{a,b}, Anna Mascherek^b, Elisa Filevich^{c,d,e}, Nina Lisofsky^{c,b}, Maxi Becker^b, Oisín Butler^c, Martyna Lochstet, Johan Mårtensson^f, Elisabeth Wenger^c, Ulman Lindenberger^{c,g} and Jürgen Gallinat^b

^aLise Meitner Group for Environmental Neuroscience, Max Planck Institute for Human Development, Berlin, Germany; ^bClinic and Polyclinic for Psychiatry and Psychotherapy, University Clinic Hamburg-Eppendorf, Hamburg, Germany; ^cCenter for Lifespan Psychology, Max Planck Institute for Human Development, Berlin, Germany; ^dBernstein Center for Computational Neuroscience Berlin, Berlin, Germany; ^eInstitute for Psychology, Humboldt-Universität zu Berlin, Berlin, Germany; ^fFaculty of Medicine, Department of Clinical Sciences Lund, Logopedics, Phoniatrics and Audiology, Lund University, Lund, Sweden; ^gMax Planck UCL Centre for Computational Psychiatry and Ageing Research, Berlin, Germany

ABSTRACT

Objectives: The effects of nature on physical and mental health are an emerging topic in empirical research with increasing influence on practical health recommendations. Here we set out to investigate the association between spending time outdoors and brain structural plasticity in conjunctions with self-reported affect.

Methods: We established the Day2day study, which includes an unprecedented in-depth assessment of variability of brain structure in a serial sequence of 40–50 structural magnetic resonance imaging (MRI) acquisitions of each of six young healthy participants for 6–8 months ($n = 281$ MRI scans in total).

Results: A whole-brain analysis revealed that time spent outdoors was positively associated with grey matter volume in the right dorsolateral prefrontal cortex and positive affect, also after controlling for physical activity, fluid intake, free time, and hours of sunshine.

Conclusions: Results indicate remarkable and potentially behaviorally relevant plasticity of cerebral structure within a short time frame driven by the daily time spent outdoors. This is compatible with anecdotal evidence of the health and mood-promoting effects of going for a walk. The study may provide the first evidence for underlying cerebral mechanisms of so-called green prescriptions with possible consequences for future interventions in mental disorders.

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Introduction

At the present time, adults spend 80–90% of their time indoors (Klepeis et al. 2001; Kirchner et al. 2009). This constitutes a fairly recent evolutionary development, likely related to the urbanisation processes observed over the last centuries. A growing body of research on this mostly indoor-based population reveals that exposure to natural environments, but also time spent outdoors, without further discrimination whether the time was spent in natural or urban environments, is beneficial to health¹. In the previous literature, time spent outdoors was negatively associated with the risk of chronic disease in adults (Beyer et al. 2018) and children (Lingham et al. 2020). Likewise, there is evidence for a link to mental health, as spending time outdoors increases well-being in adolescents (Belanger et al. 2019) and reduces

depressive symptoms in adults (Kerr et al. 2012). Whether spending time outdoors is beneficial for the brain, has not been investigated so far. However, this link might be crucial since almost all psychiatric diseases are related to brain atrophies (Goodkind et al. 2015) and the prescription to go out into the green receives more and more attention in the field (Kondo et al. 2020; Robinson et al. 2020). What has been shown is that people living in urban environments spend less time outdoors than those living in rural areas (Bodekaer et al. 2015; Matz et al. 2015). Having been raised in cities in turn has been associated with lower volume and thickness of the dorsolateral prefrontal cortex (DLPFC) (Haddad et al. 2015; Besteher et al. 2017; Lammeyer et al. 2019; Kühn et al. 2020). These differences between urban and rural upbringing have so far been mostly attributed to city life being

CONTACT Simone Kühn ✉ kuehn@mpib-berlin.mpg.de Lise Meitner Group for Environmental Neuroscience, Max Planck Institute for Human Development, Berlin, Germany

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more stressful (Lederbogen et al. 2011). However, since time spent outdoors also differs substantially between rural and urban populations (next to other parameters, such as exposure to air pollution, traffic noise), our goal was to unravel how day-to-day variations of healthy individuals in time spent outdoors might be associated with variations in brain structure. Based on the previous literature demonstrating that being raised in cities is associated with lower DLPFC volume (Haddad et al. 2015; Besteher et al. 2017; Lammeyer et al. 2019; Kühn et al. 2020), we had the *a priori* hypothesis that grey matter in DLPFC would be positively associated with time spent outdoors.

Methods and materials

Within the scope of the Day2day study (Filevich et al. 2017), we investigated six medication-free, healthy, and currently, urban-living individuals (age 24–32 years, one male, all living in Berlin) on 40–50 measurement points, distributed over 6–8 months with magnetic resonance imaging (MRI). Participants were working at the Max Planck Institute for Human Development, where the data was assessed at the MRI scanner at a time of participants' convenience and not according to a strict schedule. Most participants were scanned about twice a week, between summer 2013 and early 2014.

The Ethics Committee of Charité University Clinic, Berlin, approved of the study, including the fact that the participants were employee members of the institute. Our rationale for this was 2-fold; firstly, we thought that scientists working with MRI regularly can anticipate best what it is like to be in the scanner that regularly and know the typical data handling in science well enough to be able to consent or dissent to it, and also to sharing the data with other scientists. Secondly, it seemed much more feasible and reasonable to ask individuals who were working around the lab already, to participate, because the life changes caused by participating in this study were much lower for members of our institutes, who are regularly pilot subjects for MRI studies anyways. The study was conducted in accordance with the Declaration of Helsinki.

On each MRI assessment day we collected self-reported time spent outdoors ('How much time did you spend outdoors in the last 24 h?' (in hours)). In addition, we also asked the participants for fluid intake ('How much did you drink in the last 24 h?' (in litres)), amount of free time ('How much spare time did you have during the last 24 h?' (in hours)), amount of caffeinated drinks ('How many cups of caffeinated drinks

did you have during the last 24 h?' (in cups) and also 'during the last 2 h'), amount of physical exercise ('How many hours did you engage in physical exercise during the last 24 h?' (in hours)). Likewise, a momentary affect questionnaire (Positive and Negative Affect Schedule, PANAS) (Watson et al. 1988) and physical activity tracking device, which measured the number of steps (Fitbit One, San Francisco, USA) on a daily basis were assessed. To capture seasonality differences, hours of daily sunlight were obtained from the German Weather Service (<http://www.dwd.de/>).

To relate our findings to the previous effects of urban upbringing, the so-called urbanicity score (Pedersen and Mortensen 2001; Lederbogen et al. 2011; Haddad et al. 2015) was computed. The score assumes a constant gradient between years lived in cities with more than 100,000 inhabitants (coded as '3'), towns with 10,000–100,000 inhabitants (coded as '2'), and rural regions with <10,000 inhabitants (coded as '1'), as it multiplies the coding with the years, participants report to have lived in the respective environment.

MRI acquisition

Brain structural MRI data using a 3D T1-weighted magnetisation prepared gradient-echo sequence (MPRAGE) (repetition time (TR) = 2500 ms; echo time (TE) = 4.77 ms; TI = 1100 ms, acquisition matrix = $256 \times 256 \times 176$, flip angle = 7° ; $1 \times 1 \times 1$ mm voxel size) was obtained on a 3 Tesla Tim Trio (Siemens, Erlangen).

Voxel-based morphometry

We obtained grey matter volume estimates using CAT12 running with SPM12 and Matlab using default parameters (<http://www.neuro.uni-jena.de/cat12/CAT12-Manual.pdf>). CAT12 automatically performs intra-subject realignment, bias correction, segmentation, and normalisation. Segmentation into three voxel classes (grey matter, white matter, and cerebrospinal fluid) was performed using adaptive maximum *a posteriori* segmentation and partial volume segmentation. The extracted grey matter maps were smoothed using an FWHM kernel of 8 mm.

Processing included several stages of quality checking: Images were visually inspected for artefacts before further processing. Then, statistical quality control based on inter-subject homogeneity after segmentation was conducted. The rater was blinded to the other data and this particular research question.

Statistical analysis

On the resulting smoothed grey matter maps a whole-brain linear regression analysis was computed using *neuropointillist* (<http://ibic.github.io/neuropointillist/>; Madhyastha et al. 2018). *Neuropointillist* is an R tool-box that enables to read in neuroimaging data, compute statistics with custom-made R code on every single voxel, output results and reassemble the data into the neuroimaging (MNI) space. We ran a whole-brain multiple regression *lm()* from the *nlme* package with subject as a fixed factor using only hours spent outdoors as a predictor. First, because this was our *a priori* hypothesis, and we only later tried to enter other variables, which we reasoned could explain the observed effects (sunshine duration, amount of fluid intake, amount of free time, or physical activity) within the scope of a more exploratory analysis. Second, when entering the additional covariates in the whole-brain model, the model did not converge in every voxel of the brain. Therefore, the covariates were applied later on the grey matter volume extracted from the significant cluster. The resulting brain images were thresholded with a voxel threshold of $p < 0.00015$ and a cluster threshold of 101 adjacent voxels, determined using the latest 3dClustSim implementation of AFNI (two-sided test, alpha 0.05) to correct for multiple comparisons.

Results

Applying a multiple regression framework, we found that time spent outdoors during the last 24 h predicted momentary positive affect around the time of the MRI assessment ($\beta = 0.068$, $t = 2.63$, $p = 0.009$, adjusted $R^2 = 0.961$), but not negative affect ($\beta = -0.023$, $t = -1.08$, $p = 0.282$) (controlling for the dependency of data by entering participants as dummy coded regressors). To test whether the observed effect was driven by confounding factors, such as sunshine duration, amount of fluid intake, amount of free time, or physical activity, these variables were added as covariates. However, hours spent outdoors remained a significant predictor ($\beta = 0.081$, $t = 2.55$, $p = 0.011$), but hours of free time ($\beta = -0.030$, $t = -2.85$, $p = 0.005$) and sunshine duration ($\beta = 0.016$, $t = 2.23$, $p = 0.027$) were likewise predictive of positive affect, whereas the amount of liquid ($\beta = 0.185$, $t = 0.46$, $p = 0.68$) and physical activity ($\beta = 0.000007$, $t = 0.87$, $p = 0.39$) was not significant (adjusted $R^2 = 0.963$).

In a whole-brain analysis, relating regional grey matter volume to hours spent outside, we observed a

significant positive association between hours spent outdoors and a single cluster in the right dorsolateral prefrontal cortex (DLPFC, 18, 52, 26; 105 voxels, Brodmann area 9, Figure 1). When treating the subject as a random factor in the analysis, the result was the same in right DLPFC, however, the model did not converge for all voxels in the brain. Therefore, we reverted to reporting the results of the model treating subject as a fixed factor. The same phenomenon occurred when we added all of the covariates mentioned below. To test for effects of sunshine duration, amount of fluid intake, amount of free time, or physical activity on the present results, a multiple regression predicting the mean grey matter volume estimate of the extracted cluster was computed. None of the additional regressors reached significance (amount of fluid intake: $\beta = 0.0005$, $t = -0.06$, $p = 0.95$; physical activity: $\beta = -0.00000019$, $t = -1.18$, $p = 0.23$; hours of free time: $\beta = 0.00019$, $t = 0.92$, $p = 0.35$; sunshine duration: $\beta = 0.00016$, $t = 1.09$, $p = 0.28$), while hours spent outdoors remained a significant predictor of DLPFC grey matter ($\beta = 0.0015$, $t = 2.35$, $p = 0.019$, adjusted $R^2 = 0.9996$). The variance explained by hours spent outside amounted to 3%.

However, DLPFC grey matter volume was not associated with positive affect ($p = 0.418$) and it was not a mediator of the relationship between hours spent outdoors and positive affect (standardised indirect effect = 0.0007 with a confidence interval ranging from -0.0027 to 0.0071).

Upon visual inspection, the urbanicity score of the participants' upbringing (Table 1) did not seem to be related to the intercept of the DLPFC volume plotted in Figure 1C.

In a *post-hoc* analysis, we investigated the effects of the time of the day at which the MRI scan was obtained, since we previously reported the effects of time of the day on global MRI measures on the same data, where the variable explained $\sim 1\%$ of the variance (Karch et al. 2019). However, time of the day was not a significant predictor, neither for DLPFC grey matter ($p = 0.898$), nor for positive affect ($p = 0.086$). Moreover, it did not change the general pattern of results presented here.

Discussion

Daily variation in time spent outdoors was associated with positive (Belanger et al. 2019), but not negative affect. The absence of an association between hours outdoors and negative affect may be explained by the fact that negative affect scores were left-skewed, and

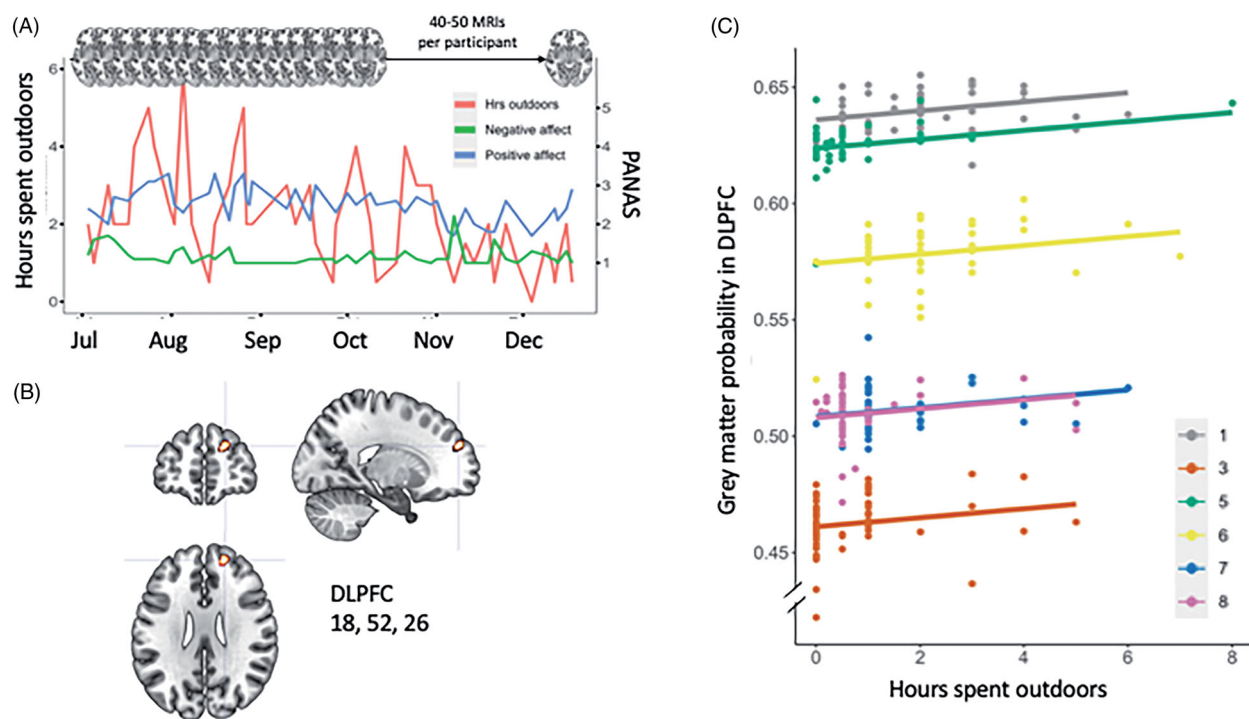


Figure 1. (A) Illustration of the data collected from a single subject, (B) cluster in the dorsolateral prefrontal cortex (DLPFC) showing a positive association between grey matter probability and self-reported hours spent outdoors, and (C) for illustrative purposes only, we plot a line graph depicting the regression of the extracted grey matter values of each subject from DLPFC (right), the y-axis has a break, as indicated by the break symbol.

Table 1. Characterisation of the study participants (SD in brackets).

ID ^a	1	3	5	6	7	8
Weight at inclusion into study (kg) ^b	58.1	68.8	64.9	63.0	72.3	59.7
Mean body weight (kg) ^b	59.4 (0.83)	69.0 (0.83)	63.5 (0.72)	63.1 (0.68)	71.8 (0.71)	59.2 (0.46)
Mean hours physical activity ^c	0.13 (0.32)	0.22 (0.55)	0.35 (0.77)	1.55 (1.04)	0.51 (0.76)	0.21 (0.55)
Mean liquid intake (l) ^c	1.86 (0.43)	2.12 (0.70)	1.68 (0.76)	2.81 (0.86)	3.38 (0.93)	1.50 (0.57)
Mean number of alcoholic drinks ^c	0 (0)	0 (0)	0 (0)	0.57 (1.5)	0.66 (1.56)	0.18 (0.65)
Mean number of caffeinated drinks ^c	0.02 (0.14)	6 (1.63)	1.68 (1.54)	1.70 (1.50)	2.08 (1.02)	1.51 (1.10)
Mean number of caffeinated drinks last 2 h	0 (0)	0.96 (0.39)	0.68 (0.91)	0.18 (0.49)	0.28 (0.60)	0.40 (0.61)
Mean number of cigarettes ^c	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0.03 (0.16)
Urbanicity score during first 15 years in life	33	15	45	30	33	15

^aThe participant ID is based on the numbering used in the protocol paper of the Day2day study (Filevich et al. 2017).

^bWeight was measured with clothing.

^cDuring the last 24 h before MRI scanning.

that values were overall quite low ($M = 1.82$). Also, the present sample was considerably younger than the sample of older adults living in retirement communities, in which depressive symptoms were reported to be lower with greater outdoor exposure (Kerr et al. 2012). Generally, our finding may be seen as in line with the results of a meta-analysis on the beneficial effects of nature exposure, observing more pronounced associations with positive than with negative affect (McMahan and Estes 2015). However, the present study did not discriminate between time spent outside in nature vs. other more urban contexts.

Most strikingly, and independently of affect, we observed that more hours spent outdoors was associated with higher grey matter volume in DLPFC. We then searched for factors potentially associated with spending time outdoors, that may also have a positive effect, or that could constitute a potential mechanism by which time spent outdoors may substantiate in more grey matter volume in DLPFC. It came as a surprise to us that none of these covariates, namely sunshine duration, amount of fluid intake, hours of free time, or physical activity, explained variance in DLPFC volume. A factor that we were not able to enter as a

covariate, and that may potentially explain the observed effect, is air pollution. It is well-known that air pollution is oftentimes worse indoors compared to outdoors, when the air is not well-ventilated, which can seriously affect the health of the inhabitants (Leung 2015; WHO 2021). This could potentially explain the positive effects of spending time outdoors on the brain and affect. However, further studies are needed in which the exact time and location of outdoor exposure are assessed so that it can be related to air pollution measurements, ideally combined with devices measuring indoor air quality.

To some degree, the present association between time spent outdoors and DLPFC volume may align with the previous studies reporting an association between urban upbringing and lower DLPFC structure (Haddad et al. 2015; Besteher et al. 2017; Lammeyer et al. 2019; Kühn et al. 2020), since it has been reported that urban inhabitants spent less time outdoors (Bodekaer et al. 2015; Matz et al. 2015). However, further data is needed assessing *where* participants spent the time outdoors (nature vs. urban context), to draw a stronger link to the previous literature. In the present sample of only six participants, whom we also asked for the environment in which they were brought up, the intercept (Figure 1C) did not seem to reflect a strong impact of rural vs. urban upbringing. But this may not come as a surprise in a small population where the goal was to investigate within-subject variability.

The present findings clearly go beyond previous results by showing that even ecologically valid daily variations in time spent outdoors are linked to DLPFC volume, not only long-term exposures to certain environments (Haddad et al. 2015; Besteher et al. 2017; Lammeyer et al. 2019; Kühn et al. 2020).

The association between time spent outdoors and DLPFC volume might also be interpreted in the light of previous studies investigating the effects of nature exposure on cognitive functioning, assuming that participants indeed spent most of the time outdoors in nature (which remains to be investigated). Two meta-analyses have demonstrated that outdoor nature interventions, but also exposure to photos and video material depicting nature can lead to improvements in cognitive domains, such as cognitive flexibility and working memory (Ohly et al. 2016; Stevenson et al. 2018). All cognitive functions, that have previously been linked to the prefrontal cortex (Yuan and Raz 2014).

To investigate this association further, future studies could use GPS tracking to dissect *where* individuals

spend their time outdoors to disentangle the effects of green and urban spaces (and with this air pollution). It is noteworthy that green space exposure has been positively related to well-being in individuals who show lower DLPFC activity during negative emotion processing (Tost et al. 2019), a finding that underlines the potential link between DLPFC function and responses to spending time outdoors.

The fact that we found a change of grey matter in DLPFC in the magnitude of 3% is in line with many experimental studies in which participants have been exposed to interventions, known to be beneficial for the brain, e.g. physical exercise or cognitive training, where gains are usually around 2–5% grey matter volume (for a review, see Lövdén et al. 2013). It is therefore remarkable that we find effects of a similar size in this more naturalistic study design assessing daily variations.

The fact that we observe day-to-day variations in brain structure may seem at odds with the assumption that brain structure, measured using structural MRI, is usually considered to be a relatively stable trait characteristic. However, there is increasing evidence hinting at short-term alterations of brain structure within the range of hours (Tost et al. 2010; Mansson et al. 2020).

A limitation of the present study is the small and selective sample. The participants did not engage in excessive nicotine, alcohol, and or drug consumption, which precludes the control of these variables. Along a similar line, we observed a significantly negative effect of hours of free time onto positive affect, which may seem striking. The participants were all working in academia which oftentimes implies that scientists identify with their work and may find rewarding. Therefore, free time might stand in less contrast to working time. However, future studies are needed that pursue a similar in-depth longitudinal study design but with more variability in the habits, professional backgrounds, and levels of physical fitness of the participants. Another limitation is that the present study was not interventional. To draw stronger causal conclusions, a research design in which spending time outdoors is experimentally manipulated would be needed.

To summarise, the present finding underlines the importance of how and in which environments (indoor vs. outdoor) we spend our daily lives. Further research is needed to explore the mechanistic link between outdoor exposure and brain structural fluctuations, where the influence of exposure to natural environments and air pollution may be of interest. Moreover,

it would be highly relevant to test for potential cognitive effects of time spent outdoors. Since psychiatric disorders have consistently been associated with prefrontal structural deficits (Goodkind et al. 2015), so-called outdoor prescriptions (Kondo et al. 2020) might be a helpful means to counteract these neural alterations and improve mood. Based on the relevance of prefrontal functions in our society at large, policies aimed at increasing time spent in the outdoors, on a population level, might be an interesting implication of the present finding.

Note

1. Whenever we refer to time spent outdoors, we refer to literature that does not differentiate between exposure to natural or urban environments.

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Disclosure statement

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Data availability statement

The data has been shared and can be shared with scientists interested in it upon request to the first author.

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