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Trees for brains: Current residential tree cover density and its association with brain structure in young adults

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ABSTRACT

Previous research has suggested an association between living environment during the first 15 years of life and brain structure. More precisely, urbanicity during upbringing has been shown to be negatively related to prefrontal cortex grey matter. The present study focusses instead on the *current* living environment of 677 younger

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adults recruited from different cities across Europe. We observed a positive association between amount of tree cover density, in a radius of 500m around the *current* home address and grey matter volume in right orbitofrontal cortex (rOFC). Of note, the volume of the rOFC cluster identified, showed a positive association with cognitive performance in the Wechsler Adult Intelligence Scale, namely in the verbal and spatial ability domain (Vocababulary, Block Design), and a negative association with both, self-reported and behavioural markers of impulsivity (delay discounting). Moreover, rOFC volume showed a negative association with self-reported alcohol use problems. The data provide strong evidence in favour of a link between geographical features of the current living environment (particularly trees) and brain structure above and beyond childhood and upbringing. Interestingly, the respective brain correlates are associated with cognitive, behavioural and personality characteristics which have been considered as risk factors for several psychiatric disorders. Environmental neuroscience may in the long run provide a knowledge base for evidence-based urban landscape planning to facilitate mental health.

The world is currently undergoing substantial changes due to climate change and its associated impact on our physical environment, with potentially more drastic alterations lying ahead of us. Another process that has been ongoing for a while is the increase in urbanization. While our ancestors were primarily living in rural areas, since around 2010, more humans are living in urban areas when considering the entire world population. The United Nations predict that by 2050 68% of the world's population will live in cities. Researchers have been concerned with the potential consequences for physical and mental health. Overall in terms of physical health, prevalence rates of e.g. diabetes, coronary heart disease (O'Connor & Wellenius, 2012) as well as all-cause mortality (Probst et al., 2020) are lower in urban areas. This stands in stark contrast to disorders of mental health, which seem to occur more frequently in urban as compared to rural areas (Peen, Schoevers, Beekman, & Dekker, 2010). In particular, the exposure to urbanicity during upbringing has been frequently related to a higher risk of developing schizophrenia (Pedersen & Mortensen, 2001). In response to this observation, psychiatrists and neuroscientists became interested in potential associations between what has been called urbanicity during upbringing and brain structure (Besteher, Gaser, Spalthoff, & Nenadic, 2017; Haddad et al., 2015; Lammeyer, Dietsche, Dannlowski, Kircher, & Krug, 2019). Taken together, the present evidence suggests that more years spent in urban living environments during the first 15 years of life are associated with lower lateral prefrontal brain structural markers such as grey matter volume (Haddad et al., 2015; Lammeyer et al., 2019) and cortical thickness (Besteher et al., 2017). However, in these aforementioned studies, the living environments are characterized on a dimension from urban to rural, therefore it might well be that the reported association could result from the rural exposure fostering brain plasticity in prefrontal cortex, rather than urban exposure negatively affecting prefrontal cortex (S. Kühn et al., 2021). A third option however, could be that certain brain preconditions lead to the selection of certain living environments, a phenomenon also termed "selective migration".

A previous study on school children in Barcelona highlighted the potential benefitial effects of green exposure reporting a positive association between trees in a 200m radius around the childrens' home addresses during upbringing and grey matter volume in the lateral prefrontal cortex (Dadvand et al., 2018). However, it may also be relevant to investigate whether the acute living environment, instead of the environment during upbringing, is likewise associated with brain structure. In a study on older participants from the Berlin Aging Study-II, the amount of forest within a 1 km radius around the current home address was positively associated with amygdala integrity (S. Kühn et al., 2017). In line with the idea that the negative association between the prefrontal cortex and urbanicity may be, to some extent, the other side of the coin namely a positive association between green spaces and prefrontal cortex, we observed a negative correlation between an area in the pregenual anterior cingulate cortex and higher coverage of the land use category urban fabric, characterized by sealed soil in the same data set. At the same time, we observed a positive correlation in an overlapping brain region with the land use category urban green in a radius of 1 km around the home address of these older adults (S. Kühn et al., 2021). Interestingly, when we entered both factors, urban fabric and urban green, into the same model, urban green still explained additional variance above and beyond urban fabric.

The question we want to address in the present work is, whether the associations observed between acute living environment and brain structure only appear in older adults, who are more likely to have lived in the same environment for long periods of time, or whether these associations can also be observed in younger adults.

This question is of particular relevance since so far, the focus of psychiatric research has been on exploring the potentially detrimental brain effects of urban upbringing, and searching for explanations for the seemingly heightened risk of schizophrenia in cities. If, however, the current living environment also reveals similar associations with brain structure, the living environment may in fact be relevant for brain health across the entire lifespan, which might open windows of opportunities for interventions targeting the current living environment.

1. Materials and methods

1.1. Participants

We used data from 677 young adults recruited within the scope of the IMAGEN project (n ≈ 2200 at Baseline), a European multi-centre (Berlin, Hamburg, Dresden, Mannheim, Nottingham, Dublin, London, Paris) genetic-neuroimaging study on adolescents (Schumann, et al., 2010). Written informed consent was obtained from all participants. Originally, the adolescents were recruited via secondary schools. The study was approved by the respective local ethics committees. We selected the 677 participants based on their participation in the MRI assessment at follow-up III and their provision of address information (age: 22.1 years, SD = 0.67, 357 females). Since Paris and Hamburg did not contribute address information, those sites are not part of the present analysis.

1.2. Tree cover density (TCD)

TCD maps were provided by the European Environment Agency Copernicus Land Monitoring Service. TCD provides information on the proportional crown coverage per pixel at 20m × 20m spatial resolution and ranges from 0% (non-tree covered areas) to 100%, whereby TCD is defined as the vertical projection of tree crowns to a horizontal earth's surface. The maps rely on information derived from multispectral high resolution (HR) satellite data using very high resolution (VHR) satellite data and/or aerial ortho-imagery as reference data. TCD is assessed on VHR sources by visual interpretation following a point grid approach on images acquired from March to October and subsequently transferred to the HR data by a linear function. We extracted mean TCD from three buffers with a radius of 500 m, 1 km and 2 km (Fig. 1). We chose the lowest radius to be 500 m because the longitude and latitude information of the participants home address was rounded to two decimals for data protection reasons, which means the location information has a

resolution of about 1 km.

1.3. Urbanicity score

In a questionnaire at follow-up II, where participants were around 22 years of age, participants were retrospectively asked how many years during their first 15 years of life they had spent living in rural areas, towns with more than 10.000 inhabitants, or towns/cities with more than 100.000 inhabitants. Based on this data we computed the so-called urbanicity score, which has been common practice in previous studies (Besteher et al., 2017; Haddad et al., 2015; Simone Kühn et al., 2020; Lederbogen et al., 2011; Pedersen & Mortensen, 2001), which multiplies years lived in cities with more than 100.000 inhabitants by three, years lived in towns with 10.000–100.000 inhabitants by two, and rural regions with less than 10.000 inhabitants by one, thereby assuming a continuous gradient of urbanicity, based on population denisty, across all living environments.

1.4. Cognitive testing and delay discounting task

The Wechsler Adult Intelligence Scale (WASI-IV) (Wechsler, Coalson, & Raiford, 2008) was used to assess cognitive performance. The following subtests were included: Block Design, Similarities, Vocabulary, and Matrix Reasoning.

Block Design involves putting together red-and-white blocks in a pattern to match to a displayed model and requires attention, spatial reasoning and response selection.

The *Similarities* task examines the ability to think abstractly and find similarities among words or ideas that may not appear to be similar on the surface.

The *Vocabulary* task measures world knowledge and the ability to express definitions of words. The words are presented visually and orally.

Matrix Reasoning is a task that is presented visually and measures non-verbal abstract problem solving, inductive reasoning and spatial reasoning ability. It requires pattern recognition and attention to visual details. Participants are asked to pick one image out of five that fits in the missing square of a shown array of pictures.

For all tasks, higher scores indicate superior performance.

Additionally, we used data from the Kirby *Delay-Discounting* Questionnaire (Kirby & Marakovic, 1996), a monetary choice questionnaire assessing cognitive impulsivity through delay discounting by having participants choose between smaller immediately available rewards and larger delayed rewards. The parameter k estimated discounting rates separated for small, medium and large rewards. It reflects the steepness of the discounting function; a steeper decrease in value is indicative of a higher amount of impulsivity in discounting decisions.

1.5. Questionnaires

The *Barratt Impulsiveness Scale-11 (BIS)* is a measure of impulsiveness that includes 30 items with three subscales which have previously been identified by means of factor analysis: attentional, motor and non-planning impulsiveness (Patton et al., 1995). All items are answered on a 4-point Likert-scale (“rarely/never”, “occasionally”, “often”, “almost always/always”). Higher scores signify higher impulsiveness.

The *Temperament Character Inventory (TCI-R)* (Cloninger, Svrakic, & Przybeck, 1993) is a self-rating personality questionnaire with the scale impulsiveness as one of the novelty seeking facets. Answers are given by means of a 5-point Likert scale (“definitely false”, “mostly false”, “neither true or false”, “mostly true”, “definitely true”). By adding up the scores of the nine items of interest, a total was computed with higher values signifying higher impulsiveness.

The *Substance Use Risk Profile Scale (SUPRS)* (Woicik, Stewart, Pihl, &

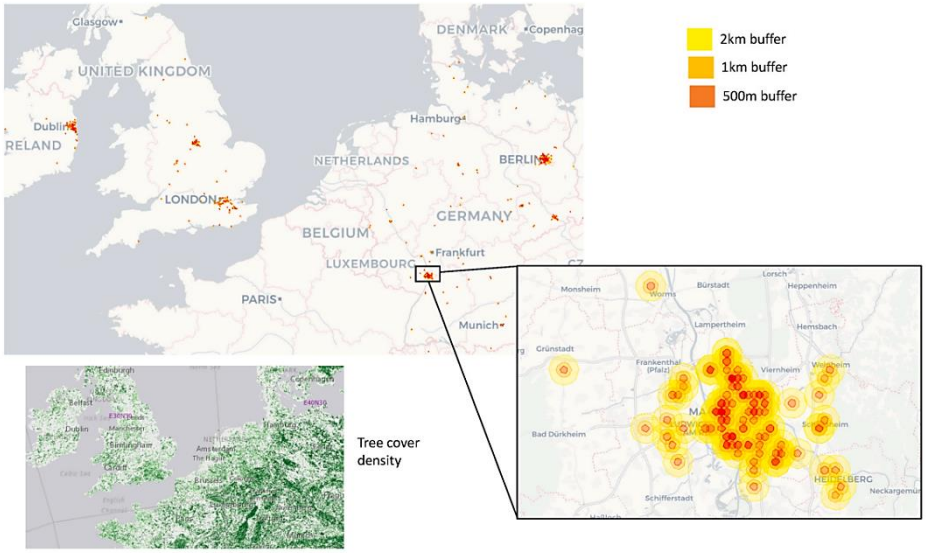

Fig. 1. Graphical display depicting buffers around the geo-coordinates on the top left and bottom right (zoom into region of Mannheim) and tree cover density as provided by the European Environment Agency Copernicus Land Monitoring Service on the bottom left.

Conrod, 2009) contains 21 items and is based on a model of personality risk for substance abuse. It discriminates four personality dimensions: hopelessness, anxiety sensitivity, impulsivity, and sensation seeking. Answers are given on a 4-point Likert scale (“strongly disagree”, “disagree”, “agree”, “strongly agree”). Higher scores signify higher manifestations of the respective dimension.

To assess alcohol drinking we used the *Alcohol Use Disorder Identification Test (AUDIT)* (Babor & Higgins-Biddle, 2001) consisting of 10 items. We computed the total score.

1.6. MRI scanning procedure

Structural MRI was performed on 3 Tesla scanners from three manufacturers (Siemens: 3 sites; Philips: 2 sites; and General Electric: 1 site). The details of the entire MR protocol are described elsewhere (G Schumann et al., 2010). In this study, we used the T1-weighted images. These high-resolution anatomical MRIs were obtained using a three-dimensional sequence based on the ADNI protocol; modified for the IMAGEN study to give a 1.1 × 1.1 × 1.1 mm^3 voxel size).

1.7. Voxel-based morphometry (VBM)

The structural MPRAGE images were processed by means of the Computational Anatomy Toolbox (CAT12; v1739) running on SPM12 in Matlab 2021a (the Mathworks, Inc., Natick, MA, USA) using default parameters. Pre-processing of the data involved intra-subject realignment, bias-field and noise removal, skull stripping, segmentation into gray (GM) and white matter (WM) and cerebrospinal fluid (CSF) using adaptive maximum a posteriori segmentation and partial volume segmentation, and finally normalization to MNI space using DARTEL to a 1.5 mm isotropic adult template provided by the CAT12 toolbox. We used the “modulated normalized” function to obtain tissue class images where the voxel values are multiplied ("modulated") with the Jacobian determinant derived from the spatial normalization, since this allows the comparison of the absolute amount of tissue (which is referred to as "volume" of gray matter (Good et al., 2001)). The extracted GM maps were smoothed using a FWHM kernel of 8 mm.

Processing included two stages of quality checking: Images were visually inspected for artefacts prior to processing and then a statistical quality control based on inter-subject homogeneity after segmentation was conducted.

We computed whole-brain multiple regression analyses. We controlled for the covariates age, sex, total intracranial volume (TIV), scanner site (dummy coded), and parental education. We used parental education as a proxy for socioeconomic status, since income was unfortunately not available neither from the participants nor from the parents of the participants from the IMAGEN study. The resulting maps were thresholded with a voxel threshold of $p < 0.001$ and a statistical extent threshold was used to correct for multiple comparisons combined with a non-stationary smoothness correction based on permutation (Hayasaka & Nichols, 2004) as implemented in the CAT12 toolbox. In addition, we also report family wise error (FWE) corrected results at $p < 0.05$. Three separate analyses were conducted with TCD in a 500 m, 1 km and 2 km radius. Significant clusters are displayed superimposed on the colin 27 average brain (ch2better (Holmes et al., 1998)) using MRIcron.

1.8. Additional statistical analyses

First, identical coordinates were jittered by adding or subtracting 0.00001 using the function jitterDupCoords() from the R package geoR, since identical coordinates cause problems in many computations targeted at assessing spatial autocorrelation. We used the function lm() to repeat the whole brain analysis on the mean of the grey matter volumes of the rOFC, controlling for the covariates mentioned above. Since regression analysis is based on the assumption that the residuals are independent and not correlated, we tested for the presence of spatial autocorrelation using the Moran’s I (Cliff & Ord, 1981; Moran, 1950) test implemented by the function lm.morantest() from the spdep package. We repeated this test twice, once employing a Euclidian distance matrix (rdist() from the fields package), and once with distance band weights as recommended in the Software package GeoDa introduced by Luc Anselin, which is a thresholded distance weight matrix with a min and max criterion representing the nearest neighbour with the shortest and longest distance so that no point has no neighbour using functions from the spdep package. Additionally, we applied the Lagrange Multiplier Test Statistics (Anselin, Bera, Florax, & Yoon, 1996; Silvey, 1959), using the function lm.LMtests() from the spdep package.

2. Results

In London we observed on average 7.70% (SD = 8.5, n = 74) tree cover density, in Nottingham 4.80% (SD = 4.4, n = 76), Dublin 5.63% (SD = 5.1, n = 129), Mannheim 7.22% (SD = 9.9, n = 144), Dresden 11.57% (SD = 9.3, n = 98) and Berlin 19.35% (SD = 13.5, n = 156) and across all sites this amounts to 10.12% (SD = 10.9, n = 677) in a 500 m radius around the home address of the participants. For the 1 km radius tree cover density was 10.79% (SD = 9.8) and for the 2 km radius 12.02% (SD = 9.4). The 500 m radius was significantly correlated with the 1 km radius ($r(677) = 0.905$) and the 2 km radius ($r(677) = 0.755$), however the standard deviation was significantly higher in the 500 m radius compared to the 1 km radius ($F = 1.24$, $p = 0.006$) and the 2 km radius ($F = 1.34$, $p < 0.001$).

2.1. Whole brain analysis

In a whole brain multiple regression analysis, we observed a significant positive association between mean tree cover density (TCD) in a radius of 500 m around the participants home and grey matter volume in right lateral orbitofrontal cortex (rOFC, MNI coordinates: 30, 42, − 9; BA11, BA47) while controlling for age, sex, TIV, scanner site and parental education (Fig. 2) and using a voxel level threshold at $p < 0.001$ and a cluster extent threshold. No significant clusters were identified that correlated negatively with tree cover density at 500 m radius and neither positive nor negative clusters were identified for TCD extracted from a radius of 1 or 2 km. When applying family wise error correction at $p < 0.05$, we do not find any significant results.

2.2. Spatial dependence

We then extracted the mean grey matter probability from the cluster in right OFC to run additional analyses to ensure that the multiple regression analysis was not confounded by spatial autocorrelation. The Moran’s I coefficient was not significant, neither when using the Euclidian distance matrix ($I = 0.92$, $p = 0.179$) nor the distance weight matrix ($I = 1.26$, $p = 0.104$). In line with this, the Lagrange Multiplier Test Statistics were all non-significant with the Euclidian distance matric as well as the distance weight matrix ($p > 0.14$). We therefore conclude that spatial autocorrelation did not confound our presented regression analysis.

2.3. Effects per site

We then conducted exploratory post-hoc correlations between grey matter volume in rOFC and TCD in the separate sites. Although the sample size was reduced at each site we still found an overall tendency for a positive association in all cities, except for London and Dublin, where the correlation coefficient was close to zero, while controlling for covariates as above (with the exception of site)(London: $r(68) = -0.079$,

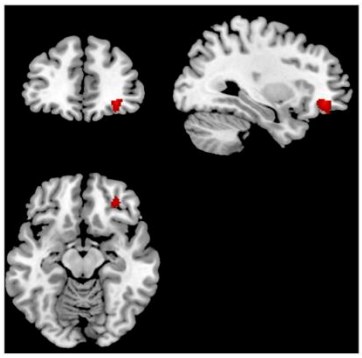

Fig. 2. Results of the voxel-based morphometry whole brain analysis in which a positive association between tree cover density (TCD) and grey matter volume was observed in the right lateral orbitofrontal cortex (MNI: 30, 42, − 9), while controlling for age, sex, total intracranial volume (TIV), scanner site and parental education.

p = 0.515, Nottingham: r(70) = 0.213, p = 0.072, Dublin: r(123) = 0.092, p = 0.308, Mannheim: r(138) = 0.157, p = 0.065, Dresden: r(92) = 0.124, p = 0.235, Berlin: r(150) = 0.235, p = 0.004).

2.4. Association with urban upbringing

In order to relate the present results to previous findings reporting on the structural neural correlates of urban upbringing in prefrontal cortex we correlated the respective urbanicity score with mean TCD in a 500 m radius while controlling for site and found no significant association between the two variables (r(492) = 0.007, p = 0.868). Since the variable was acquired at a different time point, we only had urbanicity information of n = 499 participants available. When running a linear regression analysis replacing the TCD predictor by the urbanicity score the prediction of mean rOFC grey matter volume in the cluster mentioned above by urbanicity was non-significant (β = 0.0003 p = 0.313).

2.5. Exploration of the relevance of exposure duration

In order to explore post-hoc whether the observed effect in rOFC depends on the time that participants were exposed to the respective environments we ran an exploratory analysis on the subset of participants of whom we had information about prior addresses across the entire lifespan (n = 300). For those participants we multiplied the years lived at the current address with the TCD scores. Interestingly, this exposure variable, quantifying the degree of exposure over time was not significantly associated with the extracted grey matter volume from the rOFC cluster, neither when not corrected (r(300) = 0.017, p = 0.77) nor when correcting for the covariates age, sex, TIV, scanner site and parental education (r(289) = -0.010, p = 0.86).

2.6. Association with cognitive functioning, impulsivity and alcohol drinking

In order to explore to what extent rOFC grey matter volume is associated to cognitive functioning, impulsivity and alcohol drinking, as previous literature might suggest, we conducted correlational analyses. To characterize the potential functional involvement of the rOFC in cognition, we ran a correlation on the extracted mean rOFC grey matter volume and the cognitive task performance measured in the block design (r(621) = 0.139, p < 0.001), matrix reasoning (r(620) = 0.085, p = 0.033), similarities (r(621) = 0.095, p = 0.017) and vocabulary (r (616) = 0.130, p = 0.001) task while controlling for the aforementioned control variables. When applying a conservative Bonferroni multiple test correction for this particular research question (0.05/4 = 0.0125), only the association with the block design and vocabulary task survived.

Since we have previously demonstrated an association between the rOFC and impulsivity (Schilling et al., 2013) we also investigated correlations with questionnaires assessing impulsivity, namely the BIS factors attention (r(660) = 0.016, p = 0.680), motor impulsivity (r(660) = − 0.032, p = 0.413) and non-planning (r(660) = − 0.114, p = 0.003), impulsivity as measured in TCI (r(661) = − 0.054, p = 0.164), and as operationalized in SURPS (r(661) = − 0.100, p = 0.010), as well as a delay discounting task, where the discount rate was computed for the three different reward sizes small (r(662) = − 0.141, p < 0.001), medium (r(662) = − 0.119, p = 0.002), and large (r(662) = − 0.082, p = 0.036).

When applying a conservative Bonferroni multiple test correction for this particular research question (0.05/8 = 0.00625), only the association with impulsivity as measured in SURPS and delay discounting at small and medium rate survived. Higher grey matter volume in the rOFC was associated with less impulsivity and a less steep delay discounting rate, reflecting less impulsive decisions.

Following a third direction, we associated alcohol drinking with rOFC grey matter and observed a negative association between AUDIT total score and rOFC (r(664) = − 0.083, p = 0.032).

A pairwise correlation table of the self-report and cognitive measures can be found in the supplementary material.

3. Discussion

The primary goal of the present study was to unravel potential associations between brain structure and tree cover density (TCD) in the current living environment of young adults. This research was inspired by previous studies demonstrating negative associations between years spent in more urban areas during the first 15 years of life and volume and thickness of the prefrontal cortex (Besteher et al., 2017; Haddad et al., 2015; Lammeyer et al., 2019) and a finding in which the greenness around the home addresses of school children during their upbringing was found to be positively associated with prefrontal grey matter volume (Dadvand et al., 2018). In extension to these previous findings, the present analysis was able to demonstrate similar associations between brain structure and living environment, namely that a cluster in right OFC was associated when considering the current living environment, measured by TCD in a 500 m radius around the home address in a sample of younger adults. Follow-up analyses demonstrated that this finding was not driven by spatial autocorrelations. Interestingly, when computing the association separately for the different European cities in which participants were recruited, the effect was strongest (in descending order) in Berlin, Nottingham, Mannheim and Dresden, while the effect in Dublin and London was close to zero. However, the participants were not equally distributed across the different sites, with Berlin actually having more than double the number of subjects than London, which makes a direct comparison difficult. The fact that most of the sites do show the same effect supports the validity of the finding across multiple places within Europe. In order to relate the present finding to previously reported associations between prefrontal cortex and urban upbringing we used the same urbanicity score as previously

used, but did not find a significant association with grey matter volume in the right OFC. To explore whether the current exposure to TCD is confounded with the living history at the particular place and therefore actually with a longer exposure, we computed a score weighting the TCD exposure with the number of years participants lived at that particular address. However, this weighted score was not significantly associated with the right OFC, which highlights that the observed link between TCD exposure at the home address and volume in the right OFC is indeed specific for the current exposure and likely not driven by the longer-term exposure that happened over the years that participants lived at that place. However, the sample for this latter analysis was reduced to n = 300, so this should clearly be replicated in other samples. Nevertheless, we think it is worthwhile to note that a brain structural association with features of the current physical living environment can be observed in a younger adult sample. Previous studies that reported links between the factors of the acute living environment and brain structure focussed on older adults (Crous-Bou et al., 2020; S. Kühn et al., 2017; S. Kühn et al., 2021; Nussbaum et al., 2020). The rational of focussing on older populations has often been that older adults spend more time at their home address, because they do not have the obligation to regularly leave home for school, work etc. and would therefore be more likely show these environment-brain links. The present study demonstrates that these links can also be observed in younger adults (mean age 22.1 years) that quite likely do not spend all their time at home.

The only grey matter cluster in which we observed the positive association with current TCD around the home address was located in the right OFC. The OFC has long been associated with value-based decision-making (Kringelbach, 2005; Zhou, Gardner, & Schoenbaum, 2021). A meta-analysis suggested that the medial OFC responds more strongly to reward, the lateral OFC more to punishment (Kringelbach & Rolls, 2004). Lesions in the lateral OFC inflicted on animals have been reported to result in more rapid switching behavior, even when a certain behavior was rewarded. In fact the predisposition to repeat previously successful choices seemed to be damaged after lesioning the lateral OFC (Noonan, Kolling, Walton, & Rushworth, 2012).

Since the prefrontal cortex, including the lateral OFC has been broadly associated with cognitive task performance, we tested for associations between performance measures and lateral rOFC volume in the cluster we detected. A positive relation to block design performance, matrix reasoning, similarities and a vocabulary task was found, while only block design and the vocabulary task survived a Bonferroni correction. This finding is in line with a previous study on a partly overlapping dataset, reporting brain structural correlates of impulsivity in the lateral OFC, which in turn was positively associated with block design performance (Schilling et al., 2013). Similar results were reported in a sample of schizophrenia patients and healthy controls (Schobel et al., 2009) and only in healthy controls (Nestor et al., 2010). This finding supports the relevance of the lateral OFC in cognitive performance and underlines the importance of this neural correlate of TCD exposure.

Since the lateral OFC has previously also been liked to impulsivity (Matsuo et al., 2009; Schilling et al., 2013), and a recent meta-analysis on gray matter correlates of trait impulsivity confirmed the relevance of the OFC (Pan et al., 2021), we tested for associations between grey matter volume in the rOFC and questionnaires assessing impulsivity and a task measuring impulsive decision making. In line with this notion, we observed a negative association between brain structure and impulsivity as reflected in non-planning BIS factor, SURPS and in response to all reward types in a delay discounting task, in particular with delay discounting effects in response to small and medium sized rewards. Therewith, the rOFC might be an interesting link between the previously described association between the naturalness of window views at home and lower impulsivity in female children (Taylor, Kuo, & Sullivan, 2002), or an association between nature accessibility and impulsivity in adults (Repke et al., 2018). Other studies have presented more experimental evidence demonstrating e.g. that exposure to nature pictures leads to less impulsive decisions in delay discounting (Berry et al., 2015; Berry, Sweeney, Morath, Odum, & Jordan, 2014; van der Wal, Schade, Krabbendam, & van Vugt, 2013). Future research may want to investigate whether the link between nature exposure and lower impulsivity can be mechanistically explained by an alteration of functional or structural properties of the lateral OFC.

Potentially mediated by decrements in impulsivity, the lateral OFC has also been previously associated with alcohol use related problems (Cheetham et al., 2012; Everitt et al., 2007; Lotfipour et al., 2009). It has been reasoned that an impairment of inhibition associated with the altered lateral OFC gyrification contributes to the observed vulnerability for harmful alcohol use. In line with this notion we tested this association in the present sample and observed a significant negative association between rOFC volume and the AUDIT score that quantifies problematic alcohol use.

3.1. Limitations

The present study is clearly and strongly limited by the fact that it only relies on cross-sectional data from which no causal inference can be drawn. Therefore, we cannot conclude whether the TCD in the home environment elicited the observed alterations in the rOFC or conversely, whether those alterations facilitated the self-selection into certain living environments. To determine this, longitudinal studies that track changes in living environment and associate them with changes in brain structure and ideally intervention studies that would assess the effects of planting new trees in residential areas against a control group are needed. Moreover, future studies should investigate whether it is indeed the more proximal tree cover density that is crucial, since we only observed this effect in the 500 m (not 1 km or 2 km) radius. A major short-coming of the present data set and analysis is, that we were not able to address the role that socioeconomic variables play in the relation between the living environment and the brain, since we were not able to control for or directly model the impact of e.g. income. This is problematic, since it is quite obvious that the choice of the residential area is clearly impacted by which neighbourhood a family can afford to live in and this may in turn also be confounded with presence of crime and poverty in the respective environment. At the same time the brain and cognitive functioning has likewise been demonstrated to be associated with socioeconomic status (Hackman, Farah, & Meaney, 2010; Hackman, Gallop, Evans, & Farah, 2015).

However, compared to previous studies, the present study has a fairly large sample size with participants from different regions in Europe which ensures a certain degree of geographical breadth and hopefully replicability. Future studies may want to extend this approach to less WEIRD (Western, Educated, Industrialized, Rich, Democratic) societies to ensure that the observed effects are not culturally specific.

4. Conclusion

To summarize, the present analysis revealed a positive association between grey matter volume in right lateral OFC and TCD in a radius of 500 m around the current living address of young adults, which extends previous studies that reported relationships between urbanicity during the first 15 years of upbringing and prefrontal grey matter. This provides strong evidence in favour of a link between geographical features of the living environment and brain structure above and beyond childhood and upbringing. Interestingly the grey matter volume in the right lateral OFC was positively associated with cognitive performance in the Wechsler Adult Intelligence Scale, namely with verbal and spatial visualisation (Vocabulary, Block design) performance and negatively associated with self-report and behavioural markers of impulsivity. In line with this, right lateral OFC volume was negatively associated with self-reported alcohol use problems. Taken together the present results highlight the potential relevance of green space, and in particular of trees, in our urban environments and we anticipate that the research field of

environmental neuroscience may in the long run provide a knowledge base for evidence-based urban landscape planning.

Authors' contributions

Conceptualization: GS; Data acquisition: TB, ALWB, CB, EBQ, SD, HF, AG, HG, PG, AH, BI, JLM, MLPM, FN, DPO, TP, SM, JHF, MNS, HW, RW, GS, NV, AML, JG; Formal analysis: SK; Project administration: GS; Writing – original draft: SK; Writing - review & editing: TB, ALWB, CB, EBQ, SD, HF, AG, HG, PG, AH, BI, JLM, MLPM, FN, DPO, TP, LP, SM, JHF, MNS, HW, RW, GS, NV, AML, JG.

Declaration of competing interest

Dr. Banaschewski served in an advisory or consultancy role for eye level, Infectopharm, Lundbeck, Medice, Neurim Pharmaceuticals, Oberberg GmbH, Roche, and Takeda. He received conference support or speaker's fee by Janssen, Medice and Takeda. He received conference support or speaker's fee by Lilly, Medice, and Shire. He received royalities from Hogrefe, Kohlhammer, CIP Medien, Oxford University Press; The other authors report no biomedical financial interests or potential conflicts of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://hdl.handle.net/21.11116/0000-000D-417E-D.

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