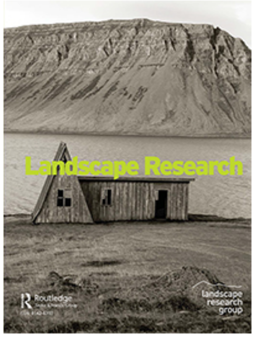


Landscape Research

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/clar20

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**To cite this article:** Eirini Flouri, Dongying Ji & Jonathan P. Roiser (2022): The role of urban greenspace in children's reward and punishment sensitivity, Landscape Research, DOI: 10.1080/01426397.2021.2021160

**To link to this article:** https://doi.org/10.1080/01426397.2021.2021160

LANDSCAPE RESEARCH
https://doi.org/10.1080/01426397.2021.2021160

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# The role of urban greenspace in children's reward and punishment sensitivity

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**ABSTRACT**
According to Life History Theory, environments with abundant and reliable resources encourage 'slow' (deliberative) strategies that are low-risk and focused on long-term outcomes. Arguably, greener neighbourhoods may approximate such environments, especially in urban settings. This study used the UK's Millennium Cohort Study to investigate the role of greenness of the child's immediate residential area at ages 9 months and 3, 5, 7, and 11 years in reward and punishment sensitivity, measured using the Cambridge Gambling Task (CGT), at age 11 years. Our sample was the children who lived in urban areas at all five time-points and with data on the CGT at the fifth (n = 5,012). Consistent with Life History Theory, we found that children in the least green areas were more likely to engage in 'fast' decision strategies than other children: they showed higher sensitivity to reward (or lower sensitivity to punishment). This association was robust to adjustment for confounders.

**KEYWORDS**
Green space; children; risk taking; gambling task

## Introduction

Risk-taking and reward-seeking are strongly related to mental health (Miu et al., 2017; Simons & Arens, 2007; Zuckerman & Kuhlman, 2000). Depression, for example, is associated with reward-processing impairments, particularly for tests of reward bias, option valuation, and reinforcement learning (Halahakoon et al., 2020). A reward-processing framework is also especially useful for understanding motivation, in turn associated with many health, educational and socio-economic outcomes (Eccles et al., 1998). How people evaluate potential rewards and punishments and use this information to make decisions has been extensively researched. However, we know little about how the broader environment can affect sensitivity to rewards (positive outcomes) and punishments (negative outcomes), especially in children. Life History Theory proposes that environments with abundant and reliable resources encourage 'slow' (deliberative) strategies that are low-risk and focused on long-term outcomes. Conversely, this theory posits that exposure to environmental harshness leads to a focus on the immediate future and the production of 'fast' strategies, for example, the tendency to seek quick rewarding stimuli and more risk-taking behaviours (Ellis et al., 2009).

The existing literature on the role of the broader ecology in such outcomes in children has focussed on the social context, such as the residential area's socio-economic deprivation and crime (Gonzalez et al., 2016). The role of physical elements of the residential neighbourhood in children's reward and punishment sensitivity is as yet unexamined. Neighbourhood greenspace—an

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Supplemental data for this article can be accessed here

important resource, especially in urban areas where most of the population lives—is an aspect of the physical environment that is associated with several outcomes thought to be linked to reward and punishment sensitivity, such as physical activity/exercise (Brush et al., 2020; Lakes & Hoyt, 2004; Leventhal, 2012), but also mental health and cognition. It has been widely regarded as important for improving both health (Bell et al., 2008; Bowler et al., 2010; Kondo et al., 2018; Maas et al., 2006; Rook, 2013) and cognition (Bodin et al., 2015; Dadvand et al., 2015; Flouri, Papachristou et al., 2019; Heschong Mahone Group, 2003; Kaplan, 2001; De Keijzer et al., 2016) in both adults and children. Therefore, one could plausibly expect an association between urban greenspace quantity and children's reward and punishment sensitivity.

We conducted the present study to fill this gap in knowledge. Based on Life History Theory we predicted that children in greener urban areas would show 'slower' strategies, compared to their counterparts living in less green urban areas. Using data from the UK's Millennium Cohort Study (MCS), a large population-based longitudinal birth cohort, we tested whether the quantity of greenspace in urban areas [i.e. settlements with populations of over 10,000 (Bibby & Shepherd, 2004)] could predict sensitivity to reward and punishment in children at age around 11 years, when reward and punishment sensitivity was measured in MCS. We predicted that those growing up in 'harsher' (less green) urban neighbourhood environments would show less aversion to risk and more impulsive choices; and, conversely, that those in less 'harsh' environments would show greater adjustment to risk and better quality of decision-making. We also expected that these relationships would survive adjustment for families' selection into neighbourhoods as well as children's demographic characteristics, cognitive ability and externalising ('acting-out') and internalising problems. We examined the associations in the urban MCS sample, excluding rural dwellers, because neighbourhood greenspace may be confounded with levels of rurality (White et al., 2013). At the age 11 follow-up, the majority of MCS participants (76.9%) lived in urban areas, indicating that the MCS population is heavily urban.

## Method

### *Participants*

MCS follows around 19,000 children born in 2000–02 (Joshi & Fitzsimons, 2016), from around 9 months (sweep 1) to around 3, 5, 7, 11 and 14 years (sweeps 2–6). The geography of electoral wards provided the sampling frame for MCS, which was designed to over-represent families living in wards of high child poverty across the UK, wards with high proportions of ethnic minorities in England, and the smaller UK countries (Plewis et al., 2004). Most of the information was collected through interviews with and self-completion questionnaires from the main respondent (overwhelmingly the mother) in the child's home. Ethical approval was gained from NHS Multi-Centre Ethics Committees, and parents gave informed consent before interviews took place, as did the cohort children themselves from age 11. At the age 11 sweep, 13,287 families took part in MCS. This study's analytic sample included children (singletons and first-born twins or triplets) who, as at the age 11 sweep, had lived in urban areas in the UK consistently since the beginning of MCS (at age about 9 months), and had valid data on reward and punishment sensitivity, which was measured with the Cambridge Gambling Task at age 11 years. The 5,012 children (51% male) of the sample were clustered in 263 wards and all had data on neighbourhood greenspace.

## Measures

### *Reward and punishment sensitivity, age 11*

This was measured with the Cambridge Neuropsychological Test Automated Battery (CANTAB) Cambridge Gambling Task (CGT; Cambridge Cognition, 2006). The CGT is a measure of decision-making and risk-taking behaviour to obtain rewards (i.e. explicit risk contingencies; Manes et al., 2002). It has been used extensively, but, with few recent exceptions (Hosozawa et al., 2021), typically in small samples. To our knowledge, MCS is the first general-population birth cohort study to use this or other gambling tasks during childhood assessments. The following description is based on our prior work in MCS using this task (Hosozawa et al., 2021). During the task, participants are asked to guess the location of a hidden token on a computer screen, and then gamble a proportion of their current points on their decision. Participants are presented with a row of 10 boxes (red and blue) across the top of the screen and are told that the computer has hidden a 'token' behind one of them. They have to choose a) which colour of box they believe the token is hidden behind (red or blue), and b) the number of points they want to gamble on their colour choice. The proportion of red to blue boxes (box ratio) varies during the task pseudo-randomly to assess the influence of statistical risk (probability) on decision-making. Participants start the task with 100 points and select a proportion of these points to bet on their decision (between 5% and 95%). A circle in the centre of the screen displays the current bet value, which either increases or decreases incrementally. Participants press the button when it shows the proportion of their score they would like to bet. These points are either added to, or subtracted from, their total score, depending on their decision and where the token was actually hidden. Before the formal experiment, participants are instructed with a practice phase to make sure they understand the rules. The task produces six outcome measures: 1) Risk-taking, the mean proportion of points bet on trials where the most likely outcome was chosen. Higher scores reflect higher reward-sensitivity (or lower punishment-sensitivity); 2) Quality of decision-making, the mean proportion of trials where the most likely outcome was selected; 3) Deliberation-time, the mean time (in milliseconds) taken to make a box colour response; 4) Risk-adjustment, the extent to which betting behaviour is moderated by probability. It reflects the tendency to stake higher bets on high-probability compared to low-probability trials; 5) Delay-aversion, the time participants are prepared to wait in order to place a higher or lower bet; 6) Overall proportion bet, the mean proportion of points gambled across all trials. We excluded overall proportion bet from the analysis as it was highly correlated ($r > .9$) with risk-taking. The remaining five measures are largely independent from each other and assess different aspects of decision-making (Flouri, Moulton et al., 2019).

### *Neighbourhood greenspace*

The greenspace measure in the Multiple Environmental Deprivation Index (MEDIx; http://cresh.org.uk/cresh-themes/environmental-deprivation/medix-and-medclass/), (Richardson & Mitchell, 2010, for more information) was linked to MCS to measure quantity of greenspace in the residential ward. It was estimated by using information from the Coordination of Information on the Environment (CORINE; EEA, 2000) and the 2001 Generalised Land Use Database (GLUD; Office of the Deputy Prime Minister, 2005), and has been used in previous studies using MCS (Flouri, Papachristou et al., 2019). In MCS, the percentages of ward-level greenspace have been converted to deciles. In the urban MCS sample at the age 11 sweep, the lowest decile corresponds to wards with less than 19% greenspace and the top to those with more than 80%. To assess the effect of longitudinal exposure to greenspace on children's development, we created a dichotomous variable (least exposure to greenspace or not) measuring if, by the age 11 sweep, the child had been living or not in a ward in the lowest decile of greenspace since 9 months old.

### *Covariates*

We controlled for individual—and family-level covariates related to families' selection into neighbourhoods and children's reward and punishment sensitivity. The individual covariates included sex, exact age at the assessment on the CGT, pubertal status (at least some signs of puberty vs. no signs) and ethnicity (white, black, Indian, Pakistani/Bangladeshi, mixed and other). General cognitive ability (IQ) was also controlled for given that it is related to both reward-processing (Flouri, Moulton et al., 2019) and exposure to green and natural environments (Ward et al., 2016). This was measured at age 5 (sweep 3) using the scores from a principal components analysis of the three subscales of British Ability Scales (BAS; Elliott et al., 1996), available at MCS at that sweep: Naming Vocabulary (measuring expressive language), Pattern Construction (measuring spatial problem-solving), and Picture Similarities (measuring non-verbal reasoning; Flouri, Moulton et al., 2019). The family-level covariates included residential mobility (total number of address changes since the beginning of MCS), and family socio-economic status, which we approximated by maternal education and family poverty. Maternal education was measured with a dummy variable indicating if the mother had a university degree by the end of the study period (sweep 5), and family poverty was measured with a dummy variable indicating whether or not the family's income was below the poverty line at sweep 5. We further adjusted for internalising and externalising problems at the time of measurement of the CGT (sweep 5, age about 11 years) in view of their association with both reward-processing (Bubier & Drabick, 2008; Lewis et al., 2021) and exposure to green spaces (Vanaken & Danckaerts, 2018). These were assessed with the main respondent's report of the Strengths and Difficulties Questionnaire (Goodman, 1997), which indexes children's levels of emotional symptoms, peer problems, conduct problems and hyperactivity. Internalising problems (Cronbach's α = 0.62) comprised emotional symptoms and peer problems, and externalising problems (Cronbach's α = 0.66) comprised conduct problems and hyperactivity. The neighbourhood social environment was approximated by the MCS sampling 'stratum' (type of electoral ward within UK country), in turn indexing the area's socio-economic deprivation. The '*Ethnic minority*' stratum comprises wards, in England, which, in the 1991 Census, had an ethnic minority indicator of at least 30%. That is, at least 30% of their total population fell into the two categories 'Black' (Black Caribbean, Black African and Black Other) or 'Asian' (Indian, Pakistani and Bangladeshi). The '*Disadvantaged*' stratum includes wards, other than those in the 'Ethnic minority' stratum, which fell into the upper quartile (poorest 25% of wards) of the ward-based Child Poverty Index (CPI). Finally, the *'Advantaged'* stratum includes wards, other than those falling into the 'Ethnic minority' stratum, which were not in the top quartile of the CPI.

## Analytic strategy

To examine the link between greenspace exposure and reward and punishment sensitivity among the continuously urban children of MCS, we fitted three multiple linear regression models for each of the five CGT measures we considered. In the first, a minimally adjusted, model, we only included greenspace, sex and exact age. In the second, we further adjusted for maternal education, ethnicity, poverty, residential mobility, IQ and pubertal status. In the third, we further adjusted for internalising and externalising problems. In all models, we used study-specific weights to account for the probability of nonresponse and attrition and controlled for the MCS 'stratum' to reflect the stratified sample design. There were no missing data on greenspace or the outcome variables. Missing data on the covariates were imputed using multiple imputation by chained equations (MICE), on the assumption that they were missing at random (Raghunathan, Lepkowksi, Van Hoewyk, & Solenbeger, 2001). We generated 25 imputed datasets and used Rubin's combination rules to consolidate the obtained individual estimates into a single set of multiply imputed estimates (Rubin, 1987). All models were fitted in STATA 16. We supplemented our analysis of nonlinear greenspace effects with a detailed investigation of linear associations in a subsample of children where these could be tested: children who did not move between greenspace deciles throughout the study period (N = 3,153). Finally, we carried out a supplementary analysis (see Supplementary Material). We refitted our models excluding a small sample of children with externalising problems, that is, children at risk of attention-deficit/hyperactivity disorder (ADHD), given the association of reward and punishment sensitivity and ADHD (Sørensen et al., 2017).

## Results

### *Descriptive statistics and bivariate analysis (unweighted data)*

The 5,012 children of the analytic sample were continuously urban dwellers and had valid data on greenspace and CGT. The amount of missing data in the analytic sample was low for maternal education, IQ and externalising/internalising problems, ranging from 0% to 3%. Residential mobility and pubertal status had relatively higher proportions of missing values, at 9.3% and 10.7%, respectively. The other variables did not have missing values. Table 1 shows the analytic sample's characteristics by quantity of neighbourhood greenspace. As expected, children in neighbourhoods with more greenspace were less socio-economically disadvantaged and had higher IQ scores. Families in such areas were more likely to be white and had been more residentially mobile (reflecting the tendency of UK families to move to neighbourhoods with more greenspace after children are born). On the CGT, children with more greenspace exposure during their first decade of life showed lower risk-taking, less delay aversion and slower deliberation, but also lower quality of decision-making. The five CGT variables were weakly inter-related (Table S1). The largest correlations were between risk adjustment and quality of decision-making ($r = .28$, $p < .01$) and between deliberation time and quality of decision-making ($r = -.23$, $p < .01$).

**Table 1.** Variable distribution by neighbourhood greenspace in the analytic sample (unweighted data).

| | | Low neighbourhood greenspace (bottom decile) n = 753 (15%) | High neighbourhood greenspace (other deciles) n = 4259 (85%) | *p*-value |
|---|---|---|---|---|
| Continuous variables, M(SD) | | | | |
| CGT | Risk taking | 0.55 (0.16) | 0.52 (0.17) | <.001 |
| | Risk adjustment | 0.68 (1.11) | 0.69 (1.04) | 0.73 |
| | Quality of decision-making | 0.82 (0.17) | 0.80 (0.17) | 0.03 |
| | Delay aversion | 0.30 (0.26) | 0.28 (0.26) | 0.04 |
| | Deliberation time (milliseconds) | 3243.30 (1153.92) | 3347.59 (1452.91) | 0.06 |
| | Internalising problems | 3.02 (2.89) | 3.14 (3.11) | 0.36 |
| | Externalising problems | 4.17 (3.39) | 4.45 (3.51) | 0.05 |
| Exact age | | 11.13 (0.34) | 11.17 (0.33) | <.001 |
| IQ | | 99.44 (15.62) | 101.46 (14.12) | <.001 |
| Residential mobility (number of address changes at the five sweeps) | | 0.34 (0.57) | 0.68 (0.78) | <.001 |
| Categorical variables, n (%) | | | | |
| Female | | 372 (49%) | 2105 (49%) | 0.99 |
| Pubertal signs | | 417 (63%) | 2522 (62%) | 0.65 |
| Stratum | England—Advantaged | 190 (25%) | 1398 (33%) | <.001 |
| | England—Disadvantaged | 191 (25%) | 1111 (26%) | |
| | England—Ethnic | 289 (38%) | 259 (6%) | |
| | Wales—Advantaged | 0 (0%) | 237 (6%) | |
| | Wales—Disadvantaged | 19 (3%) | 730 (17%) | |
| | Scotland—Advantaged | 49 (7%) | 198 (5%) | |
| | Scotland—Disadvantaged | 15 (2%) | 309 (7%) | |
| | Northern Ireland—Advantaged | 0 (0%) | 3 (0%) | |
| | Northern Ireland—Disadvantaged | 0 (0%) | 14 (0%) | |
| Ethnicity | White | 425 (56%) | 3768 (88%) | <.001 |
| | Mixed | 32 (4%) | 122 (3%) | |
| | Indian | 63 (4%) | 110 (3%) | |
| | Pakistani and Bangladeshi | 119 (16%) | 112 (3%) | |
| | Black or Black British | 81 (11%) | 99 (2%) | |
| | Other ethnic group | 33 (4%) | 48 (1%) | |
| Mother is university-educated | | 170 (23%) | 821 (19%) | 0.04 |
| Below the poverty line | | 203 (27%) | 697 (16%) | <.001 |

*Note*. p-values of t-tests for continuous variables and chi-square tests for categorical variables.

### Regression models

Three nested multiple linear regression models were fitted to investigate the role of long-term exposure to greenspace in children's reward and punishment sensitivity. Significant effects were observed only for risk-taking. As shown in Table 2, less exposure to greenspace was related to more risk-taking after minimal adjustment. The effect remained significant (Table 3) even after adjusting for maternal education, ethnicity, poverty, residential mobility, IQ and pubertal status (b = 0.017, SE = .008, $p$ = 0.047). The effect was robust to further adjustments for externalising and internalising problems (b = 0.018, SE = .008, $p$ = 0.026; Table 4), indicating that children in the least green areas showed higher sensitivity to reward (or lower sensitivity to punishment). As expected, boys were more sensitive to reward (or less sensitive to punishment) than girls, but the interaction term between greenspace and sex was non-significant (results not shown), suggesting that the association between greenspace exposure and risk-taking was similar across sexes. Also consistent with our expectations, externalising and internalising problems were, respectively, positively and negatively associated with risk-taking.

**Table 2.** Multiple linear regression model for risk-taking (minimally adjusted model).

| | Coef. | Std. Err. | t | P>\|t\| | [95% CI] |
|---|---|---|---|---|---|
| Greenspace: bottom decile | 0.018 | 0.008 | 2.14 | 0.033 | [0.001, 0.035] |
| Age | 0.004 | 0.008 | 0.53 | 0.596 | [−0.012, 0.020] |
| Female | −0.093 | 0.006 | −16.53 | 0.000 | [−0.104, −0.082] |
| Stratum (ref England—Advantaged) | | | | | |
| England-Disadvantaged | 0.007 | 0.008 | 0.88 | 0.377 | [−0.009, 0.024] |
| England-Ethnic | 0.022 | 0.013 | 1.69 | 0.092 | [−0.004, 0.048] |
| Wales-Advantaged | −0.014 | 0.014 | −1.03 | 0.302 | [−0.042, 0.013] |
| Wales-Disadvantaged | −0.021 | 0.011 | −1.92 | 0.057 | [−0.042, 0.001] |
| Scotland-Advantaged | 0.006 | 0.015 | 0.41 | 0.679 | [−0.024, 0.036] |
| Scotland-Disadvantaged | −0.002 | 0.014 | −0.12 | 0.902 | [−0.030, 0.026] |
| Northern Ireland-Advantaged | −0.133 | 0.101 | −1.31 | 0.191 | [−0.332, 0.067] |
| Northern Ireland-Disadvantaged | 0.136 | 0.032 | 4.28 | 0.000 | [0.073, 0.198] |
| Constant | 0.617 | 0.091 | 6.77 | 0.000 | [0.438, 0.797] |

**Table 3.** Multiple linear regression model for risk-taking (excluding externalising/internalising problems).

| | Coef. | Std. Err. | t | P>\|t\| | [95% CI] |
|---|---|---|---|---|---|
| Greenspace: bottom decile | 0.017 | 0.008 | 2.00 | 0.047 | [0.000, 0.033] |
| Residential mobility | 0.000 | 0.004 | 0.12 | 0.906 | [−0.007, 0.008] |
| Age | 0.001 | 0.008 | 0.09 | 0.927 | [−0.015, 0.017] |
| Female | −0.091 | 0.006 | −14.48 | 0.000 | [−0.103, −0.079] |
| Below the poverty line | 0.010 | 0.008 | 1.18 | 0.240 | [−0.006, 0.026] |
| Mother is university—educated | −0.005 | 0.006 | −0.73 | 0.468 | [−0.017, 0.008] |
| Pubertal signs | −0.002 | 0.007 | −0.40 | 0.689 | [−0.017, 0.011] |
| IQ | −0.001 | 0.000 | −2.33 | 0.021 | [−0.001, −0.000] |
| Stratum (ref England—Advantaged) | | | | | |
| England-Disadvantaged | 0.002 | 0.008 | 0.28 | 0.778 | [−0.014, 0.019] |
| England-Ethnic | 0.002 | 0.014 | 0.13 | 0.896 | [−0.026, 0.029] |
| Wales-Advantaged | −0.014 | 0.014 | −0.96 | 0.338 | [−0.041, 0.014] |
| Wales-Disadvantaged | −0.025 | 0.011 | −2.33 | 0.021 | [−0.047, −0.004] |
| Scotland-Advantaged | 0.007 | 0.015 | 0.45 | 0.655 | [−0.023, 0.037] |
| Scotland-Disadvantaged | −0.004 | 0.014 | −0.31 | 0.757 | [−0.033, 0.024] |
| Northern Ireland-Advantaged | −0.138 | 0.094 | −1.47 | 0.143 | [−0.323, 0.047] |
| Northern Ireland-Disadvantaged | 0.131 | 0.032 | 4.05 | 0.000 | [0.067, 0.195] |
| Ethnicity (ref 'White') | | | | | |
| Mixed | 0.019 | 0.016 | 1.20 | 0.232 | [−0.012, 0.050] |
| Indian | 0.022 | 0.016 | 1.39 | 0.167 | [−0.009, 0.053] |
| Pakistani/Bangladeshi | 0.019 | 0.014 | 1.36 | 0.176 | [−0.009, 0.046] |
| Black | 0.007 | 0.015 | 0.46 | 0.648 | [−0.023, 0.037] |
| Other | 0.014 | 0.016 | 0.88 | 0.382 | [−0.018, 0.046] |
| Constant | 0.709 | 0.096 | 7.40 | 0.000 | [0.520, 0.897] |

**Table 4.** Fully adjusted multiple linear regression model for risk-taking (including externalising/internalising problems).

| | Coef. | Std. Err. | t | P>\|t\| | [95% CI] |
|---|---|---|---|---|---|
| Greenspace: bottom decile | 0.018 | 0.008 | 2.24 | 0.026 | [0.002, 0.034] |
| Age | 0.003 | 0.008 | 0.43 | 0.669 | [−0.012, 0.019] |
| Residential mobility | −0.001 | 0.004 | −0.28 | 0.777 | [−0.009, 0.006] |
| Female | −0.084 | 0.006 | −13.32 | 0.000 | [−0.096, −0.072] |
| Below the poverty line | 0.003 | 0.008 | 0.34 | 0.734 | [−0.013, 0.019] |
| Mother is university-educated | −0.000 | 0.006 | −0.06 | 0.955 | [−0.013, 0.012] |
| Pubertal signs | −0.003 | 0.007 | −0.39 | 0.700 | [−0.016, 0.011] |
| IQ | −0.000 | 0.000 | −1.51 | 0.132 | [−0.001, 0.000] |
| Stratum (ref England-Advantaged) | | | | | |
| England-Disadvantaged | 0.002 | 0.008 | 0.20 | 0.839 | [−0.015, 0.018] |
| England-Ethnic | 0.001 | 0.014 | 0.08 | 0.933 | [−0.026, 0.028] |
| Wales-Advantaged | −0.014 | 0.014 | −1.04 | 0.300 | [−0.041, 0.013] |
| Wales-Disadvantaged | −0.025 | 0.011 | −2.37 | 0.018 | [−0.046, −0.004] |
| Scotland-Advantaged | 0.007 | 0.015 | 0.43 | 0.668 | [−0.024, 0.037] |
| Scotland-Disadvantaged | −0.004 | 0.014 | −0.25 | 0.805 | [−0.031, 0.024] |
| Northern Ireland-Advantaged | −0.110 | 0.100 | −1.11 | 0.270 | [−0.307, 0.086] |
| Northern Ireland-Disadvantaged | 0.131 | 0.036 | 3.67 | 0.000 | [0.061, 0.201] |
| Ethnicity (ref 'White') | | | | | |
| Mixed | 0.020 | 0.016 | 1.28 | 0.202 | [−0.011, 0.051] |
| Indian | 0.025 | 0.016 | 1.61 | 0.109 | [−0.006, 0.057] |
| Pakistani/Bangladeshi | 0.027 | 0.014 | 1.91 | 0.057 | [−0.001, 0.055] |
| Black | 0.012 | 0.016 | 0.80 | 0.422 | [−0.018, 0.043] |
| Other | 0.019 | 0.016 | 1.18 | 0.240 | [−0.013, 0.052] |
| Externalising problems | 0.006 | 0.001 | 6.74 | 0.000 | [0.005, 0.008] |
| Internalising problems | −0.003 | 0.001 | −2.91 | 0.004 | [−0.005, −0.001] |
| Constant | 0.630 | 0.095 | 6.65 | 0.000 | [0.444, 0.817] |

## Functional form of the greenspace 'effect'

Our analysis thus far assessed the effect of longitudinal exposure to greenspace on children's reward and punishment sensitivity. Our main variable of interest was a dummy variable (least exposure to greenspace or not) measuring if, by the age 11 sweep, the child had been living or not in a ward in the lowest decile of greenspace since 9 months old. Although it allowed us to include movers and non-movers in the sample and analysis, this approach could only test whether a nonlinear effect for greenspace was significant. However, to investigate whether the effect was linear or nonlinear (a different research question), we had to revise our existing approach. We therefore re-analysed the data after excluding those families who moved between deciles of greenspace (due to household moves). This resulted in retaining 3,153 'stayer'[1] families out of the stayer and mover 5,012 families in our analytic sample. Figure 1 shows average risk-taking score by decile of greenspace, and Table 5 additionally includes the number of children per greenspace decile in this reduced sample. As can be seen, the two greenest deciles had very low Ns (30 and 3 children).

We then explored greenspace in quintiles for the 'stayers' sample given the low N of the two greenest deciles. Figure 2 shows the average risk-taking score by quintile of greenspace, and Table 6 additionally includes the number of children per greenspace quintile.

Subsequently, we fitted regression models treating greenspace (in quintiles) as either a continuous or a categorical variable. Tables 7 and 8 show, respectively, the results from a model including greenspace in quintiles (as a continuous variable) only and from the minimally adjusted model adding sex, exact age and the MCS strata. As can be seen, the greenspace effect did not survive even minimal adjustment.

We repeated this modelling sequence (Tables 9 and 10) when treating greenspace as a categorical variable (greenest quintile as reference). As can be seen, children in the greenest quintile did not differ from children in the other quintiles in risk-taking.

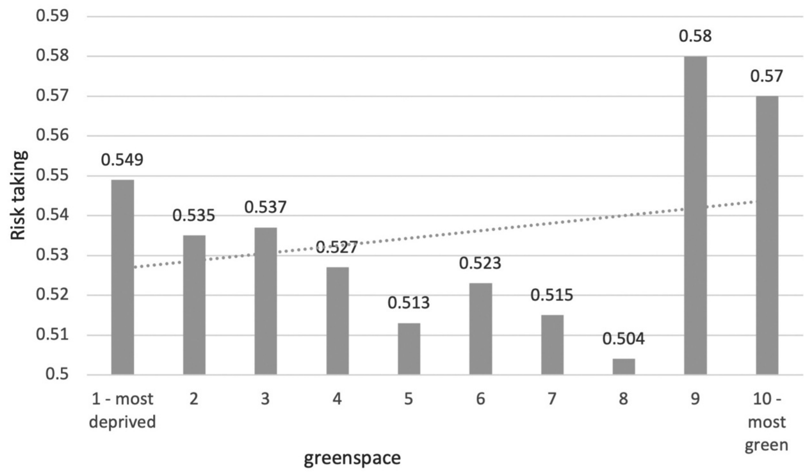


**Figure 1.** Risk-taking by greenspace decile in the 'stayers' sample (N = 3,153) (weighted data).

**Table 5.** Risk-taking by greenspace decile in the 'stayers' sample (N = 3,153) (weighted data).

| | Risk taking | N | Standard deviation |
|---|---|---|---|
| 1—least green (most deprived of greenspace) decile | 0.549 | 753 | 0.162 |
| 2 | 0.535 | 506 | 0.161 |
| 3 | 0.537 | 342 | 0.177 |
| 4 | 0.527 | 485 | 0.167 |
| 5 | 0.513 | 427 | 0.169 |
| 6 | 0.523 | 373 | 0.152 |
| 7 | 0.515 | 123 | 0.164 |
| 8 | 0.504 | 111 | 0.148 |
| 9 | 0.580 | 30 | 0.198 |
| 10—most green decile | 0.570 | 3 | 0.102 |

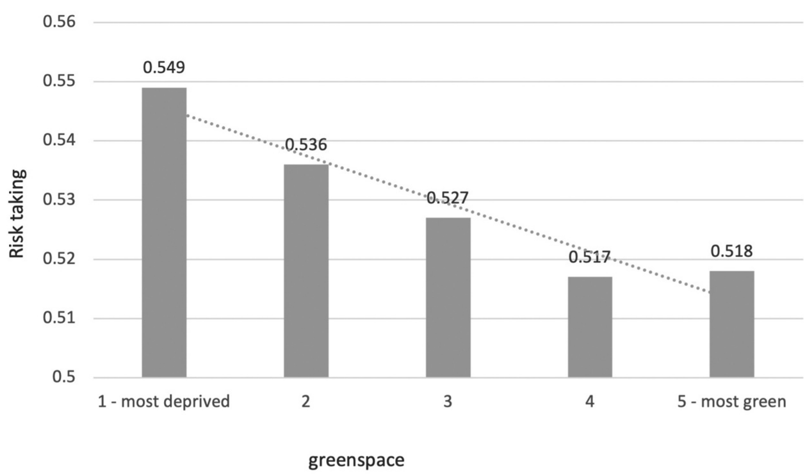


**Figure 2.** Risk-taking by greenspace quintile in the 'stayers' sample (N = 3,153) (weighted data).

We repeated this modelling sequence (Tables 11 and 12) when treating greenspace as a categorical variable but with the least green quintile as reference. As can be seen, children in the least green quintile had higher risk-taking scores than children in the fourth quintile. They also had

**Table 6.** Risk-taking by greenspace quintile in the 'stayers' sample (N = 3,153) (weighted data).

| | Risk taking | N | Standard deviation |
|---|---|---|---|
| 1—least green (most deprived of greenspace) quintile | 0.549 | 753 | 0.162 |
| 2 | 0.535 | 848 | 0.168 |
| 3 | 0.527 | 485 | 0.167 |
| 4 | 0.517 | 800 | 0.162 |
| 5—most green quintile | 0.518 | 267 | 0.162 |

**Table 7.** Risk-taking by greenspace (in quintiles) in the 'stayers' sample (N = 3,153); complete cases.

| | Coef. | Std. Err. | t | P>\|t\| | [95% CI] |
|---|---|---|---|---|---|
| Greenspace in quintiles | −0.009 | 0.003 | −2.88 | 0.004 | [−0.015, −0.003] |
| Constant | 0.556 | 0.009 | 61.03 | 0.000 | [0.538, 0.574] |

**Table 8.** Risk-taking by greenspace (in quintiles) in the 'stayers' sample (N = 3,153); minimally adjusted model; complete cases.

| | Coef. | Std. Err. | t | P>\|t\| | [95% CI] |
|---|---|---|---|---|---|
| Greenspace in quintiles | −0.006 | 0.003 | −1.70 | 0.090 | [−0.012, 0.001] |
| Age | −0.001 | 0.011 | 0.12 | 0.906 | [−0.024, 0.021] |
| Female | −0.091 | 0.006 | −14.69 | 0.000 | [−0.103, −0.079] |
| Stratum (ref England—Advantaged) | | | | | |
| England-Disadvantaged | 0.004 | 0.011 | 0.37 | 0.709 | [−0.018, 0.026] |
| England-Ethnic | 0.039 | 0.014 | 2.86 | 0.005 | [−0.012, 0.065] |
| Wales-Advantaged | −0.007 | 0.019 | −0.04 | 0.970 | [−0.037, 0.036] |
| Wales-Disadvantaged | −0.012 | 0.014 | −0.85 | 0.397 | [−0.039, 0.015] |
| Scotland-Advantaged | 0.026 | 0.016 | 1.57 | 0.119 | [−0.007, 0.058] |
| Scotland-Disadvantaged | −0.002 | 0.016 | −0.16 | 0.875 | [−0.033, 0.028] |
| Constant | 0.694 | 0.127 | 5.47 | 0.000 | [0.444, 0.944] |

**Table 9.** Risk-taking by quintile of greenspace (greenest quintile as reference) in the 'stayers' sample (N = 3,153); complete cases.

| | Coef. | Std. Err. | t | P>\|t\| | [95% CI] |
|---|---|---|---|---|---|
| Greenspace (most green quintile as reference) | | | | | |
| Quintile 4 | −0.001 | 0.018 | −0.07 | 0.942 | [−0.036, 0.033] |
| Quintile 3 | 0.009 | 0.022 | −0.42 | 0.677 | [−0.034, 0.052] |
| Quintile 2 | 0.017 | 0.018 | 0.94 | 0.346 | [−0.019, 0.054] |
| Quintile 1 (least green) | 0.031 | 0.017 | 1.79 | 0.075 | [−0.003, 0.065] |
| Constant | 0.518 | 0.016 | 32.31 | 0.000 | [0.487, 0.550] |

**Table 10.** Risk-taking by quintile of greenspace (greenest quintile as reference) in the 'stayers' sample (N = 3,153); minimally adjusted model; complete cases.

| | Coef. | Std. Err. | t | P>\|t\| | [95% CI] |
|---|---|---|---|---|---|
| Greenspace (most green quintile as reference) | | | | | |
| Quintile 4 | −0.008 | 0.016 | −0.52 | 0.603 | [−0.040, 0.023] |
| Quintile 3 | 0.002 | 0.021 | −0.10 | 0.919 | [−0.043, 0.039] |
| Quintile 2 | 0.004 | 0.017 | 0.23 | 0.819 | [−0.029, 0.037] |
| Quintile 1 (least green) | 0.016 | 0.017 | 0.97 | 0.334 | [−0.017, 0.049] |
| Age | −0.002 | 0.011 | −0.14 | 0.892 | [−0.024, 0.021] |
| Female | −0.091 | 0.006 | −14.60 | 0.000 | [−0.104, −0.079] |
| Stratum (ref England—Advantaged) | | | | | |
| England-Disadvantaged | 0.004 | 0.011 | 0.37 | 0.714 | [−0.018, 0.026] |
| England-Ethnic | 0.036 | 0.013 | 2.65 | 0.009 | [0.009, 0.062] |
| Wales-Advantaged | −0.001 | 0.019 | −0.07 | 0.942 | [−0.038, 0.036] |
| Wales-Disadvantaged | −0.011 | 0.014 | −0.75 | 0.457 | [−0.039, 0.018] |
| Scotland-Advantaged | 0.025 | 0.017 | 1.47 | 0.142 | [−0.009, 0.059] |
| Scotland-Disadvantaged | −0.002 | 0.017 | −0.17 | 0.868 | [−0.036, 0.031] |
| Constant | 0.679 | 0.128 | 5.30 | 0.000 | [0.427, 0.932] |

**Table 11.** Risk-taking by quintile of greenspace (least green quintile as reference) in the 'stayers' sample (N = 3,153); complete cases.

| Greenspace (least green quintile as reference) | Coef. | Std. Err. | t | P>\|t\| | [95% CI] |
|---|---|---|---|---|---|
| Quintile 2 | −0.014 | 0.011 | −1.34 | 0.180 | [−0.033, 0.063] |
| Quintile 3 | −0.022 | 0.016 | −1.34 | 0.182 | [−0.054, 0.010] |
| Quintile 4 | −0.032 | 0.011 | −3.06 | 0.002 | [−0.053, −0.011] |
| Quintile 5 (most green) | −0.031 | 0.017 | −1.79 | 0.075 | [−0.065, 0.003] |
| Constant | 0.549 | 0.007 | 83.67 | 0.000 | [0.536, 0.562] |

**Table 12.** Risk-taking by quintile of greenspace (least green quintile as reference) in the 'stayers' sample (N = 3,153); minimally adjusted model; complete cases.

| Greenspace (least green quintile as reference) | Coef. | Std. Err. | t | P>\|t\| | [95% CI] |
|---|---|---|---|---|---|
| Quintile 2 | −0.012 | 0.011 | −1.09 | 0.276 | [−0.034, 0.010] |
| Quintile 3 | −0.018 | 0.017 | −1.04 | 0.297 | [−0.052, 0.016] |
| Quintile 4 | −0.024 | 0.012 | −2.07 | 0.039 | [−0.048, −0.001] |
| Quintile 5 (most green) | −0.016 | 0.017 | −0.97 | 0.334 | [−0.049, 0.017] |
| Age | −0.002 | 0.011 | −0.14 | 0.892 | [−0.024, 0.021] |
| Female | −0.091 | 0.006 | −14.60 | 0.000 | [−0.104, −0.079] |
| Stratum (ref England—Advantaged) | | | | | |
| England-Disadvantaged | 0.004 | 0.011 | 0.37 | 0.714 | [−0.018, 0.026] |
| England-Ethnic | 0.036 | 0.013 | 2.65 | 0.009 | [0.009, 0.062] |
| Wales-Advantaged | −0.001 | 0.019 | −0.07 | 0.942 | [−0.038, 0.036] |
| Wales-Disadvantaged | −0.011 | 0.014 | −0.75 | 0.457 | [−0.039, 0.018] |
| Scotland-Advantaged | 0.025 | 0.017 | 1.47 | 0.142 | [−0.009, 0.059] |
| Scotland-Disadvantaged | −0.003 | 0.017 | −0.17 | 0.868 | [−0.036, 0.031] |
| Constant | 0.695 | 0.128 | 5.45 | 0.000 | [0.444, 0.947] |

higher scores than children in the greenest quintile (a small number of children compared to those in the other quintiles; see, Table 6), but the difference was not significant. These findings suggest that, to the extent that we could test for the functional form of the greenspace effect in the selective and reduced sample of urban stayers in MCS across the first 10 years of the cohort, contextual greenery appeared to have a threshold effect on child risk-taking. Together with the findings from the analysis in the full sample these results suggest that, in children, the association between greenspace and risk-taking is nonlinear; the relative absence of contextual greenery is associated with increased risk-taking but its increased quantity is not associated with reduced risk-taking.

## Supplementary analysis

Our supplementary analysis was a sensitivity analysis excluding children at risk of ADHD in our analytic sample. As no clinical diagnosis for ADHD was available in MCS, we fitted models 1–3 after excluding those children (n = 647) scoring, at age 11 years, above cut-off on the hyperactivity subscale of SDQ, which has been shown to detect cases with ADHD among youths meeting criteria for other disorders as well as discriminate cases with ADHD from those without ADHD among the general youth population (Algorta et al., 2016). The greenspace effect on risk-taking remained significant across all three models (Tables S2, S3 and S4).

## Discussion

This study investigated, in a large urban sample in the UK, the association between quantity of neighbourhood greenspace and children's reward and punishment sensitivity, measured with a gambling task. Specifically, it explored if reward and punishment sensitivity, measured using the Cambridge Gambling Task (CGT) around the beginning of adolescence (age 11), was associated with living in urban neighbourhoods with the least greenspace availability since birth. We expected that children growing up in the least green urban areas would show less aversion to risk, less adjustment to risk, lower quality of decision-making and more delay aversion than other urban children. We found some support for our hypothesis. Even after adjusting for neighbourhood and family socio-economic disadvantage but also important individual characteristics such as pubertal status, IQ and mental health, children in the least green urban areas showed higher sensitivity to reward than other urban children. Although the effect was small it is substantively important. It suggests that limited availability in urban areas of natural or semi-natural areas, partially or completely covered by vegetation, that provide habitat for wildlife and can be used for recreation (such as parks, woodlands and allotments) is related not only to health outcomes but also to an important component of decision-making, the process of choice under risk. Our supplementary analysis on the sub-sample of stayer urban families additionally showed that, in children, the relative absence of contextual greenery is associated with increased risk-taking rather than its increased quantity with reduced risk-taking. As to how low quantity of greenspace in the neighbourhood may be related to children's risk-taking, elucidating the possible mechanisms underlying this relationship was beyond the scope of our study, but future research could investigate them in detail. A plausible pathway, for example, could be physical activity/exercise (Brush et al., 2020; Lakes & Hoyt, 2004; Leventhal, 2012).

Although Life History Theory has been tested in now classic studies of links between characteristics of the local ecology and various life-history outcomes (Gilbert et al., 2016), ours was the first study to be guided by it in order to explore the role of the physical rather than the social local context in these outcomes in children. In urban areas, where more than half of the population worldwide lives [and where nearly 70% will live by 2050 (United Nations, 2018)], greenspace is a valuable resource associated with many health and cognitive benefits. Mechanisms thought to lead to these benefits include psychological relaxation and stress alleviation, greater opportunity for physical activity and lower exposure to air pollutants, noise and excess heat. In our decidedly urban country of study (82% of the UK population is now living in urban environments), we took urban neighbourhoods with very little availability of greenspace to approximate the type of environments that Life History Theory would associate with 'fast strategies'. Guided by Life History Theory and recent research examining how stress affects dopaminergic reward-processing brain regions, which shows that stress enhances learning about positive outcomes but impairs learning about negative outcomes of choices (Mather & Lighthall, 2012), we tested this prediction in the children of the Millennium Cohort Study.

Our study has some important limitations. First, it is correlational, and so it remains unclear if the association between living in areas with little greenspace and increased reward sensitivity is causal and not due to unmeasured confounding. For instance, we did not consider the role of other contexts whose characteristics are associated with both urban neighbourhoods'

greenspace and children's cognitive skills and risk-taking, such as schools (Wu et al., 2014), which we could not consider in this study. Second, our measure of greenspace used data from 2001 to characterise quantity of greenspace a decade later. Although in our analysis we took into account changes in neighbourhood greenspace due to residential moves, we did not account for changes in the characteristics of neighbourhoods over time. However, there is evidence that in the UK area deprivation and other area characteristics do not change substantially over 10 years in recent history (Gambaro et al., 2016; Kontopantelis et al., 2018). Third, we had no data on the quality of greenspace and different types of greenness which may be more relevant than percentage of green cover for the outcomes we considered. Related to this, environmental factors, such as noise and air pollution, intrinsically linked to both quality and quantity of greenspace, could be on the causal pathway for our outcomes and therefore could be usefully examined in future research. Fourth, we had no data on access and use of green spaces. Fifth, we did not consider the greenspace available in adjacent areas, which children, especially those living near ward boundaries, could also access. Sixth, we must acknowledge the possibility of Type 1 error. Finally, the CGT has some limitations. The risk-taking measure is likely related to both reward seeking and punishment avoidance; these factors cannot be disentangled due to the task design, as the potential wins and losses were always identical. Similarly, lower betting when the odds of winning are high, which will reduce the risk adjustment measure, might occur either because participants find rewards less valuable or because they are motivated to avoid losses.

Nonetheless, the study also has significant strengths, including the use of data from a large and nationally representative cohort, the longitudinal recording of exposure to greenspace and the measurement of reward and punishment sensitivity in very early adolescence. The findings of this study contribute to our understanding of the 'net' role of greenspace in children's decision-making, which is itself related to many important life outcomes. Urban planners should note that access to nature may not only benefit people's health and cognition but also affect their motivational style and reward processing, as suggested here. Our results could also be useful for policymakers when translating research evidence into targeted interventions, such as increasing greenness at schools and around the residential neighbourhood, to improve children's outcomes.

## Conclusions

Using data from a large, general-population birth cohort in the UK we showed that children living in the least green urban neighbourhoods showed 'faster' strategies than other urban children. The association was not large but was robust to stringent adjustment for confounders. It suggests that the built environment can impact on risk-taking among children as young as 11 years old. Future research should explore why children in less green urban areas show less aversion to risk, and how urban environments could be designed to protect from dysfunctional reward-related decision-making in the general child population.

## Note

1. 'Stayers' here are those families who did not change greenspace decile across the study period. This sample therefore does not exclude families who moved home but stayed in the same ward or families who moved home and ward but for whom the ward of destination and that of origin were in the same greenspace decile.

## Acknowledgments

This research was funded by a grant from the UK Economic and Social Research Council (grant number ES/N007921/1) and a grant from the UCL Institute of Mental Health

## Disclosure statement

No potential conflict of interest was reported by the author(s).

## Funding

This work was supported by the Economic and Social Research Council [ES/N007921/1].

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