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The relationship between natural outdoor environments and cognitive functioning and its mediators

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17 Title  
18 The relationship between natural outdoor environments and cognitive functioning and its mediators  
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48

49

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## 61 COMPETING FINANCIAL INTERESTS DECLARATION

62 The authors declare they have no actual or potential competing financial interests.

63 ABSTRACT

64 Background

65 Urban residents may experience cognitive fatigue and little opportunity for mental restoration due to a  
66 lack of access to nature. Natural outdoor environments (NOE) are thought to be beneficial for cognitive  
67 functioning, but underlying mechanisms are not clear.

68 Objectives

69 To investigate the long-term association between NOE and cognitive function, and its potential mediators.

70 Methods

71 This cross-sectional study was based on adult participants of the Positive Health Effects of the Natural  
72 Outdoor Environment in Typical Populations in Different Regions in Europe (PHENOTYPE) project.  
73 Data were collected in Barcelona, Spain; Doetinchem, the Netherlands; and Stoke-on-Trent, United  
74 Kingdom. We assessed residential distance to NOE, residential surrounding greenness, perceived amount  
75 of neighborhood NOE, and engagement with NOE. Cognitive function was assessed with the Color Trails  
76 Test (CTT). Mediation analysis was undertaken following Baron and Kenny.

77 Results

78 Each 100m increase in residential distance to NOE was associated with a longer CTT completion time of  
79 1.50% (95% CI 0.13, 2.89). No associations were found for other NOE indicators and cognitive function.  
80 Neighborhood social cohesion was (marginally) significantly associated with both residential distance to  
81 NOE and CTT completion time, but no evidence for mediation was found. Nor were there indications for  
82 mediation by physical activity, social interaction with neighbors, loneliness, mental health, air pollution  
83 worries, or noise annoyance.

84 Conclusions

85 Our findings provide some indication that proximity to nature may benefit cognitive function. We could  
86 not establish which mechanisms may explain this relationship.

87

88 Keywords: Natural outdoor environments; green space; cognition; mediation; environmental  
89 epidemiology; built environment

## 90 INTRODUCTION

91 Natural outdoor environments (NOE) are places with natural ('green and blue') elements such as parks,  
92 forests, and recreation areas. Contact with natural outdoor environments has been suggested to be beneficial  
93 to human health and wellbeing [1]. However, a large proportion of the world's population currently lives  
94 in urban areas, where they are often deprived of contact with nature. One particular concern of city living  
95 is that residents may experience more stress than rural residents [2,3], making them more vulnerable to  
96 developing mental illnesses [4]. Urban environments contain many stimuli that require directed attention  
97 due to, for example, traffic and crowding. Directed attention refers to the effortful, conscious attention for  
98 focusing on specific stimuli, while avoiding distractions. As a result, urban residents may experience more  
99 cognitive fatigue and little opportunity for mental restoration [5].

100 The attention restoration theory (ART) proposes that directed attention, i.e. attention directed by cognitive  
101 control processes, is restored by interaction with nature. Natural environments are thought to have minimum  
102 requirements for directed attention, allowing for directed attention functions to restore [6]. According to  
103 another theory, the stress reduction theory (SRT), nature helps to decrease stress by lowering states of  
104 arousal and negative thoughts. Natural places with certain characteristics (e.g. visible horizons for spotting  
105 of predators, availability of food) are from an evolutionary perspective better for survival, and may  
106 automatically evoke positive responses [7].

107 Evidence for a relation between NOE and improved cognitive function mainly originates from experimental  
108 studies typically focusing on short-term exposures (for a review, see [5]). Studies have observed  
109 improvements in memory capacity and attention after walking in natural environments, compared to  
110 walking in urban environments [8–12]. Other studies have evaluated visibility of NOE and relations with  
111 cognition; it has been found that people with a window facing a green space reported less concentration  
112 problems than those without a green view [13], and that people were less likely to be forgetful and  
113 disorganized [14]. Similarly, students with the most natural window view had better directed attention than  
114 those with built or concrete window views [15]. Even viewing pictures of natural environments resulted in  
115 improved scores on attention tests [8,16]. Other observational studies evaluating the beneficial effects of  
116 access to NOE on cognition have for example focused on working memory and behavioral development in  
117 children [17,18] and on cognitive function and dementia in older adults [19,20]. A recent review  
118 summarizing these studies reported that the number of available studies are limited and concluded that  
119 current evidence for such an association is inadequate [21].

120 While most of the previous research focused on cognition benefits associated with NOE visibility, more  
121 indirect pathways may also be relevant to explore. Access to NOE may affect cognition indirectly by  
122 encouraging physical activity [22], facilitating social interaction [23], and by improving mood [24], which  
123 may all be beneficial for cognitive function [25,26]. Conversely, in environments with little nature,  
124 residents may be increasingly exposed to air pollution [27] and traffic noise [28]. The exposure to air  
125 pollutants and noise and related worries and annoyance may influence cognitive functions [29–32].

126 There is, however, little evidence of the mechanisms underlying the relation between cognitive function  
127 and NOE. Evidence about the duration of these effects and its causality is also lacking. Another unresolved  
128 question is what type of interaction with NOE is needed for beneficial cognition effects. While most  
129 previous observational studies focused on residential distance to nature or surrounding greenness, the actual  
130 engagement with and perceived amount of nature in ones surroundings may also be important [33].

131 To gain further insight into the relation between long-term exposure to nature and cognitive function, we  
132 investigated the association between multiple NOE indicators and performance on the Color Trails Test  
133 (CTT), which assesses attention and executive function. We also evaluated the potential mediating roles of  
134 physical activity, social interaction, mental health, air pollution worries, and noise annoyance.

135

## 136 **METHODS**

### 137 *Study design and participants*

138 The study was undertaken within the Positive Health Effects of the Natural Outdoor environment in Typical  
139 Populations in different regions in Europe (PHENOTYPE) project. This project was established to  
140 investigate the relationship between exposure to NOE and health and its underlying mechanisms in a sample  
141 of residents from four European cities: Barcelona (Spain); Doetinchem (the Netherlands); Kaunas  
142 (Lithuania); and Stoke-on-Trent (United Kingdom) [34]. Participants were recruited from 30  
143 neighborhoods per city that were selected in order to have variability in access to natural outdoor  
144 environments and socioeconomic status. From these neighborhoods, a random sample of 30-35 adults aged  
145 18-75 were invited to participate, resulting in a sample of around 1000 participants per city (response rates  
146 were 46.9% in Barcelona; 8.4% in Doetinchem; 21.3% in Kaunas; and 36.9% in Stoke-on-Trent, see further  
147 details in [35]). Data were collected alongside a face-to-face questionnaire administered at participants'  
148 residences during May-November 2013. In Kaunas (Lithuania), data were collected using a postal

149 questionnaire and for this reason the CTT (our measure of cognitive function) could not be assessed in  
150 participants from Kaunas. Therefore, in the current study, only data from Barcelona, Doetinchem, and  
151 Stoke-on-Trent were used. All participants provided written informed consent and study protocols were  
152 approved by the local ethical committees.

153 A total of 1628 participants completed the CTT. From this sample, participants with incomplete data  
154 regarding indicators of the natural environment (n=83), mediators (n=222), and covariates (n=26) were  
155 excluded from the corresponding analyses, leaving between n=1493 and n=1602 participants for the current  
156 analyses depending on the exposure and mediator (see Tables 2-5).

157

### 158 *Characterization of the natural outdoor environment*

159 NOE were characterized with data using geographical information systems (GIS) and face-to-face  
160 questionnaires [34]. Participants' residential addresses were collected and subsequently geocoded.

161 - Residential distance to NOE was based on Urban Atlas 2006 [36] (Barcelona and Stoke-On-Trent) and  
162 Top10NL [37] (Doetinchem) databases. Both databases use a 1:10,000 scale and a minimum  
163 represented unit of 0.25ha (Top10NL was adapted to be consistent with Urban Atlas). The Euclidean  
164 distance from residences to natural spaces >1 hectare [38] was calculated for the following land use  
165 categories: green urban areas (e.g. public gardens, parks) (14100), agricultural land, semi-natural areas,  
166 wetlands (20000), forests (30000), water bodies (50000) [39].

167 - Residential surrounding greenness was assessed with the normalized difference vegetation index  
168 (NDVI). The NDVI is a measure of level of vegetation in a certain area and was derived from satellite  
169 images available from Landsat 8 at a resolution of 30 m × 30 m. We aimed to find cloud-free images  
170 within the greenest season (May to September) in the relevant period for this study (2011-2013), and  
171 obtained images from 16th April 2013 (Barcelona area), 21st July 2013 (The Netherlands East), and  
172 21st April 2011 (Stoke-on-Trent). The NDVI is based on the fact that healthy vegetation absorbs most  
173 visible light and reflects large parts of near-infrared light, while sparse vegetation reflects more visible  
174 light and less near-infrared light. Based on this distinction and excluding large water bodies, a value  
175 between -1 and +1 was calculated, with higher values indicating higher density of green vegetation [40].  
176 The average NDVI values were calculated within (Euclidean) buffers of 100m, 300m, and 500m around  
177 the residence, as was done in previous research [33,41].



- 178 - Perceived amount of neighborhood NOE was assessed with questions ‘How would you describe your  
179 a) neighborhood, b) street c) window view in terms of green or blue space’ with answers on a five-point  
180 scale ranging from ‘not at all’ (1) to ‘very’ (5). With these questions a sum score of a, b and c questions  
181 was calculated with higher scores indicating a higher degree of nature in the neighborhood.
- 182 - Visits to NOE was assessed with questions ‘How often did you visit a green or blue space in the last 4  
183 weeks on purpose a) near your home, b) in your city, c) close to your city’ with answers on a five-point  
184 scale ranging from ‘never’ (1) to ‘(almost) daily’ (5).
- 185 - Total time spent visiting NOE was calculated by combining data on the number of visits to NOE (see  
186 above) with questions: ‘How much time did you spend in a green or blue space a) near your home, b)  
187 in your city, c) close to your city in the last four weeks’, with answers on a 4-point scale ranging from  
188 <1 hours (1) to 6-10 hours (4). Middle values of each answer category for frequency (e.g. <1  
189 times/month was coded as 0.5 times/month) were multiplied with middle values of each answer category  
190 for duration (e.g. <1 hours/month was coded as 0.5 hours/month) and summed.

191

### 192 *Cognitive function*

193 Cognitive function was assessed with the Color Trails Test (CTT). The CTT is a language- and culture-free  
194 neuropsychological test that measures visual attention, and effortful executive processing abilities [42]. The  
195 test consists of numbered coloured circles from 1 to 25 in pink and yellow. Participants are required to  
196 rapidly connect the circles in sequence, but to alternate between the pink and yellow colors. Such a task is  
197 thought to be demanding for sustained and divided attention, and poorer CTT results have been reported in  
198 ageing populations [43] and in clinical populations with impaired cognitive function [44].

199 The CTT was completed at the participant’s home, after the completion of the structured face-to-face  
200 questionnaire. Completion time and errors were recorded by the interviewer. Both were used as outcomes  
201 in the current study, with shorter completion time and fewer errors reflecting better cognitive function.

202 Participants had 5 minutes to complete the test; if after 5 minutes the test was not completed, a CTT time  
203 of 300 seconds was recorded. CTT test quality was recorded by the interviewer after completion of the test.

204 For example, if the participant had raised the pencil from the paper during the test, this was rated as ‘poor  
205 quality.’

206

### 207 *Mediators*

- 208 - Physical activity was assessed with questions from the Short Questionnaire to Assess Health-enhancing  
209 physical activity (SQUASH) [45]. Total minutes per week of active commuting (walking and biking)  
210 and being physically active during leisure time were calculated and summed.
- 211 - Social interaction with neighbors was assessed with the question ‘How often do you have contact with  
212 your neighbors?’ and was scored on a 5-point scale ranging from ‘at least once a week’ (1) to ‘seldom  
213 or never’ (5), and was dichotomized into  $\geq 1$  per month and  $< 1$  per month.
- 214 - Loneliness was assessed with six statements based on the UCLA loneliness scale (e.g. feelings of  
215 isolation, feeling as part of a group of friends) [46]. Participants were asked to indicate to what extent  
216 they agreed with the statements on a 5-point scale ranging from ‘totally agree’ (1) to ‘totally disagree’  
217 (5). A sum score was calculated with higher scores indicating greater feelings of loneliness.
- 218 - Neighborhood social cohesion was assessed with the Social Cohesion and Trust Scale, consisting of 5  
219 items (e.g. ‘people are willing to help their neighbors’) [47]. Questions were scored on a 5-point scale  
220 and a sum score was calculated with higher scores indicating a higher degree of social cohesion.
- 221 - Perceived mental health was assessed with 5 questions from the Medical Outcome Study Short Form  
222 (SF-36) mental health subscale, assessing nervousness and feelings of depression in the past month.  
223 Questions were scored on a 6-point scale ranging from ‘all of the time’ (1) to ‘none of the time’ (6). A  
224 sum score was calculated and transformed into a scale ranging from 0 to 100 according to guidelines  
225 [48] with higher scores indicating better mental health.
- 226 - Traffic noise annoyance was assessed with one question about the degree of annoyance caused by traffic  
227 noise, which was scored on a scale ranging from ‘not annoyed at all’ (0) to ‘extremely annoyed’ (10)  
228 [49]. The response scale was transformed into a scale from 0 to 100, and a score of  $> 72$  was considered  
229 being highly annoyed by traffic noise [50].
- 230 - Worry about air pollution was assessed by asking to what extent participants were worried that the air  
231 pollution in their neighborhood could lead to health problems. Worries could be indicated on a scale  
232 ranging from ‘not worried at all’ (0) to ‘extremely worried’ (10). Participants were considered to be  
233 worried about air pollution when they scored  $> 7$ .

234

### 235 *Covariates*

236 Covariates were chosen a priori based on previous literature [33,42,51]. Data on sex, age, educational level  
237 (primary school or no education; secondary school/ further education (up to 18 years); university degree or

238 higher), time spent away from home, and start date of residence at the current address were obtained from  
239 face-to-face questionnaires. Neighborhood socioeconomic status (low; intermediate; high) was based on  
240 country-specific data, and CTT test quality (good; poor) was recorded by the interviewer.

241

#### 242 *Statistical analysis*

243 Descriptive statistics were calculated for the total study population and separately for each of the three  
244 cities. Parametric and non-parametric tests were used to test for significant differences between cities. To  
245 account for clustering within cities and neighborhoods, associations were analyzed with multilevel analysis  
246 with a random intercept defined at the city and neighborhood level. City-specific associations between the  
247 NOE indicators and CTT were also investigated to evaluate differences between cities.

248 Mediation analysis was undertaken in four steps following Baron and Kenny (1986) and previous research  
249 [33]. Conditions for mediation are that the predictor variable (NOE) must affect the mediator; and that the  
250 mediator must affect the outcome variable (CTT); and that the association between the predictor and  
251 outcome is eliminated or weakened when the mediator is included in the model.

252 1. The association between NOE and cognitive function. Linear and logistic multilevel models with  
253 random intercept for city and neighborhood were developed separately for CTT completion time (log  
254 transformed for normal distribution) and CTT errors (no errors/ 1 or more error(s)) as outcomes.  
255 Models were adjusted for age, sex, educational level, neighborhood socioeconomic status, time spent  
256 away from home, and CTT test quality.

257 2. The association between NOE and mediators. Multilevel models with random intercept for city and  
258 neighborhood were developed in which we specified the mediators physical activity, social  
259 interaction, loneliness, neighborhood social cohesion, mental health, air pollution worries, and noise  
260 annoyance as the outcome (one at a time), and indicators of NOE as the predictor. Models were  
261 adjusted for the same covariates as specified in step 1.

262 3. The association between mediators and cognitive function. Multilevel models with random intercept  
263 for city and neighborhood were developed in which we specified the mediators (see step 2) as  
264 predictors and the CTT as outcome. Models were adjusted for the same covariates as specified in step  
265 1.

266 4. The association between NOE, mediators and cognitive function. Mediators were added to the  
267 multilevel models as specified in step 1, allowing for estimation of associations between indicators of  
268 NOE and the CTT, while adjusting for the mediators.

269 Finally, if the conditions for mediation were met, the proportion of the total effect mediated (i.e. the  
270 combined effect of the exposure and mediator divided by the effect of the exposure) was calculated to  
271 quantify the relative contribution of each mediator. The proportion and the 95% confidence interval were  
272 obtained through bootstrapping [33].

273 The analyses in step 1 were repeated while excluding participants with a poor CTT test quality (n= 38;  
274 instead of using CTT quality as a covariate) to assess robustness of our findings. We also repeated analyses  
275 in step 1 while excluding those living at their residence <1 year (n=86) to assess whether residence time  
276 affected the results.

277 In order to report results in a consistent manner, we calculated the percentage difference per one unit  
278 increase of the predictor for each of the estimates and 95% confidence intervals (except for CTT errors).  
279 For log-transformed outcome variables, we calculated the exponential of the coefficients and subsequently  
280 the percentage difference in the outcome per one unit increase of the independent variable:  $(\exp(\beta)-1)*100$   
281 [53]. For odds ratios and coefficients for untransformed outcome variables the percentage difference was  
282 calculated as  $(\text{odds ratio}-1)*100$  or  $(\beta/\text{range of outcome variable})*100$ . All analyses were performed in  
283 STATA 14.1 [54]. Associations were considered statistically significant if the 95% confidence intervals  
284 did not include zero ( $\beta$ ) or one (odds ratios).

285

## 286 **RESULTS**

### 287 *Population characteristics*

288 Population characteristics are presented in Table 1. Participants were on average 48 (SD=15.2) years old  
289 and 54.1% were female. Median CTT completion time varied significantly between cities and was longest  
290 in Barcelona and shortest in Doetinchem. Over a quarter (28.5%) of the participants made one or more  
291 errors on the CTT and this was similar across the three cities. The median residential distance to NOE was  
292 largest in Barcelona, and much smaller in Doetinchem and Stoke-on-Trent ( $p<.001$ ). Similarly, surrounding  
293 greenness was highest in Doetinchem, followed by Stoke-on-Trent, and lowest in Barcelona ( $p<.001$ ). Also  
294 the perceived amount of NOE in the neighborhood was lower in Barcelona than in the other cities ( $p<.001$ ).

295 Furthermore, participants from Doetinchem visited NOE most often ( $p < .01$ ) and spent most time there  
 296 ( $p < .05$ ), compared to participants from Barcelona and Stoke-on-Trent (Table 1). Correlations between  
 297 objective NOE measures and the perceived amount of NOE ranged from -0.58 (residential distance to NOE)  
 298 to 0.61 (residential surrounding greenness in 100m buffer). The use of NOE and objective NOE measures  
 299 were less strongly correlated, we observed for example a correlation of -0.25 between residential distance  
 300 to NOE and NOE visits, and 0.22 between residential surrounding greenness (100m buffer) and NOE visits  
 301 (all correlations  $p < .001$ ; Supplemental Material Table S1).

302

303 Table 1 Characteristics of study population

	Total (n=1628)	Barcelona, Spain (n=732)	Doetinchem, the Netherlands (n=567)	Stoke-on- Trent, UK (n=329)	p value
Females, %	54.1	52.3	57.6	51.8	>.05
Age, mean $\pm$ SD	48.1 (15.2)	44.3 (15.2)	55.6 (12.1)	43.6 (15.4)	<.001 <sup>a</sup>
Educational level, %					<.001 <sup>b</sup>
Primary school	6.6	13.4	0.9	0.9	
Secondary school	45.3	37.6	44.0	65.1	
University degree	48.1	49.0	55.1	34.0	
Neighborhood SES, %					<.05 <sup>c</sup>
Low	29.6	31.1	28.4	28.1	
Medium	35.0	31.7	39.9	33.8	
High	35.5	37.2	31.7	38.1	
CTT time (s), median (IQR)	93 $\pm$ 54	107 $\pm$ 54	83 $\pm$ 38	90 $\pm$ 61	<.001 <sup>b</sup>
CTT $\geq$ 1 errors, %	28.5	28.3	27.0	31.8	>.05
Residential distance to NOE (m), median (IQR)	119.6 (243.2)	310.2 (331.1)	45.5 (80.0)	83.2 (106.8)	<.001 <sup>b</sup>
Residential surrounding greenness, mean $\pm$ SD					
100 m buffer	0.38 $\pm$ 0.18	0.22 $\pm$ 0.09	0.54 $\pm$ 0.12	0.46 $\pm$ 0.08	<.001 <sup>b</sup>
300 m buffer	0.39 $\pm$ 0.18	0.23 $\pm$ 0.11	0.55 $\pm$ 0.09	0.49 $\pm$ 0.09	<.001 <sup>b</sup>
500 m buffer	0.40 $\pm$ 0.18	0.24 $\pm$ 0.11	0.57 $\pm$ 0.08	0.50 $\pm$ 0.09	<.001 <sup>b</sup>
Perceived amount of NOE, median (IQR)	7 (6)	5 (6)	10 (3)	7 (4)	<.001 <sup>b</sup>
NOE total visits last 4 wks, median (IQR)	11 (21)	8 (19.5)	18.5 (22)	8 (18.5)	<.01 <sup>a</sup>
NOE total time spent visiting (hours spent last 4 wks), median (IQR)	14.0 (31.5)	12.0 (30.5)	18.0 (27.8)	12.0 (44)	<.05 <sup>b</sup>
Physical activity min/week, median (IQR)	420 (580)	240 (420)	670 (570)	360 (540)	<.05 <sup>b</sup>

Social interaction neighbors <1/month, %	9.6	15.4	3.0	7.6	<.01 <sup>b</sup>
Social cohesion, mean ± SD	13.0 ± 4	12.0 ± 3.0	14.0 ± 3.1	13.2 ± 3.7	<.001 <sup>b</sup>
Loneliness, median (IQR)	11 (5)	10 (5)	10 (4)	13 (3.5)	<.05 <sup>d</sup>
Mental health, median (IQR)	80 (20)	76 (20)	84 (12)	76 (24)	<.05 <sup>b</sup>
Air pollution worries, %	23.3	40.9	7.9	10.6	<.001 <sup>e</sup>
Noise annoyance, %	14.4	23.1	6.7	8.2	<.001 <sup>e</sup>
Hours away from home (per week), median (IQR)	10 (10)	10 (11)	11 (8)	8 (10)	<.05 <sup>b</sup>

304 CTT: color trails test; NOE: natural outdoor environments; NDVI: normalized difference vegetation index;

305 SD: standard deviation; IQR: interquartile range. <sup>a</sup> NL different from SP and UK; <sup>b</sup> all groups differ; <sup>c</sup> NL

306 different from SP; <sup>d</sup> UK different from SP and NL; <sup>e</sup> SP different from NL and UK.

307

308 *Associations between natural outdoor environments and CTT*

309 Each 100m increase in residential distance to NOE was associated with a longer CTT completion time of

310 1.50% (95% CI 0.13, 2.89) (Table 2). No associations were found between any of the other indicators of

311 NOE exposure and CTT completion time. No associations were found between any of the NOE indicators

312 and CTT errors (Table 2). City-specific associations between residential distance to NOE and CTT

313 completion time were only statistically significant for participants from Barcelona (Supplemental Material

314 Table S2). Similar to the pooled analyses, city-specific associations between the other indicators of natural

315 outdoor environments and CTT completion time and CTT errors were not statistically significant, with one

316 exception: we observed a significant association between surrounding greenness (in 500 m buffer) and

317 longer CTT completion time for participants from Doetinchem (Supplemental Material Table S2).

318 Sensitivity analysis showed that exclusion of participants with a poor CTT test quality (n= 38) and those

319 with time of residence <1 year (n=86) did not change the results (data not shown).

320

321 Table 2 Associations between NOE and CTT completion time and errors

	% Difference in CTT time (95% confidence interval)	OR ≥1 CTT errors (95% confidence interval)
Residential distance to NOE (per 100 m) (n=1602)	1.50 (0.13, 2.89)	1.02 (0.97, 1.07)
Residential surrounding greenness 100 m buffer per IQR 0.313 (n=1602)	-0.60 (-7.27, 6.55)	0.93 (0.74, 1.16)
Residential surrounding greenness 300 m buffer per IQR 0.336 (n=1602)	-0.27 (-8.59, 8.81)	0.91 (0.72, 1.16)

Residential surrounding greenness 500 m buffer per IQR 0.349 (n=1602)	-1.63 (-10.53, 8.15)	0.89 (0.70, 1.13)
Perceived amount of NOE in neighborhood (n=1599)	-0.13 (-0.78, 0.51)	1.01 (0.97, 1.05)
NOE visits (n=1602)	-0.04 (-0.15, 0.08)	1.00 (1.00, 1.01)
NOE total time spent visiting (n=1567)	-0.01 (-0.04, 0.03)	1.00 (1.00, 1.00)

322 CTT: color trails test; NOE: natural outdoor environments; OR: odds ratio; IQR: interquartile range. Models  
323 were adjusted for age, sex, educational level, neighborhood socioeconomic status, time spent away from  
324 home, and CTT test quality and random intercepts were specified for cities (n=3) and neighborhoods  
325 (n=93).

326

327 ***Associations between natural outdoor environments and potential mediators***

328 No statistically significant associations were observed between residential distance to NOE and any of the  
329 potential mediators (Table 3). The association between residential distance to NOE and neighborhood social  
330 cohesion was marginally statistically significant (p=0.078) (Table 3).

331

332 Table 3 Associations between residential distance to NOE and potential mediators

	% Difference (95% confidence interval)						
	Physical activity (n=1526)	Social interaction with neighbors (n=1602)	Social cohesion neighborhood (n=1493)	Loneliness (n=1570)	Mental health (n=1590)	Air pollution worries (n=1601)	Noise annoyance (n=1602)
Residential distance to NOE (per 100 m)	1.64 (-1.30, 4.67)	-1.20 (-13.15, 12.39)	-0.60 (-1.26, 0.07)	0.91 (-0.27, 2.11)	-0.25 (-0.71, 0.22)	4.76 (-3.25, 13.43)	5.08 (-4.39, 15.48)

333 NOE: natural outdoor environments. Models were adjusted for age, sex, educational level, neighborhood  
334 socioeconomic status, time spent away from home, and CTT test quality, and random intercepts were  
335 specified for cities (n=3) and neighborhoods (n=93).

336

337 ***Associations between potential mediators and cognitive function***

338 Higher loneliness and more air pollution worries were associated with longer CTT completion time, while  
339 higher social cohesion and better mental health were related to shorter CTT completion time (Table 4).  
340 Physical activity, social interaction with neighbors, and noise annoyance were not statistically significantly  
341 associated with CTT time (Table 4).

342

343 Table 4 Associations between potential mediators and CTT time

Mediator	% Difference in CTT time
----------	--------------------------

	(95% confidence interval)
Physical activity (n=1602)	0.001 (-0.003, 0.005)
Social interaction neighbors (n=1602)	-4.10 (-9.78, 1.94)
Social cohesion neighborhood (n=1493)	-0.94 (-1.50, -0.37)
Loneliness (n=1570)	1.48 (0.93, 2.04)
Mental health (n=1590)	-0.22 (-0.34, -0.10)
Air pollution worries (n=1601)	5.43 (0.79, 10.30)
Noise annoyance (n=1602)	1.02 (-4.09, 6.41)

344 CTT: color trails test. Models were adjusted for age, sex, educational level, neighborhood socioeconomic  
345 status, time spent away from home, and CTT test quality and random intercepts were specified for cities  
346 (n=3) and neighborhoods (n=93).

347

### 348 *Associations between natural outdoor environments, mediators and cognitive function*

349 Finally, none of the potential mediators were significantly associated with both residential distance to NOE  
350 and CTT completion time. Since neighborhood social cohesion was (marginally) significantly associated  
351 with both residential distance to NOE and CTT completion time, we investigated the association between  
352 residential distance to NOE and CTT completion time, while adjusting for neighborhood social cohesion.  
353 However, in this model, the association between residential distance to NOE and CTT completion time  
354 increased slightly (Table 5). These results give no clear indication for mediation of the association between  
355 residential distance to NOE and cognitive function by neighborhood social cohesion.

356

357 Table 5 Associations between distance to NOE, neighborhood social cohesion and CTT time

	% Difference in CTT time (95% confidence interval)
Residential distance to NOE (per 100 m)	1.58 (0.19, 3.00)
Social cohesion neighborhood (n=1493)	-0.91 (-1.48, -0.35)

358 NOE: natural outdoor environments; CTT: color trails test. Model was adjusted for age, sex, educational  
359 level, neighborhood socioeconomic status, time spent away from home, and CTT test quality and random  
360 intercepts were specified for cities (n=3) and neighborhoods (n=93).

361

362

## 363 **DISCUSSION**

364 An increase in residential distance to NOE was related to longer completion time of the CTT. This may  
365 indicate that people living further away from nature have lower scores in cognitive function, specifically  
366 for visual attention, and effortful executive processing abilities. There were no associations between



367 cognitive function and (i) residential surrounding greenness, (ii) perceived amount of NOE in  
368 neighborhoods, and (iii) engagement with NOE. We found no clear indications for mediation by physical  
369 activity, social interaction with neighbors, neighborhood social cohesion, loneliness, mental health, air  
370 pollution worries, or noise annoyance.

371

372 Some of our results are in line with previous studies that also observed relations between access to NOE  
373 and cognitive function. One previous observational study that was performed in primary schoolchildren  
374 reported improvements in the development of working memory and attention after 12 months that was  
375 related to surrounding greenness in residential, school and commuting areas [17]. Another study could not  
376 find an association between proportion of parks in the neighborhood and cognitive function [19], while a  
377 UK study found surrounding greenness and private gardens to be a risk factor for cognitive impairment and  
378 dementia [20]. We are not aware of previous studies investigating the relation between access to NOE and  
379 cognitive function measured with the CTT. Most of the other previous studies had an experimental design  
380 and assessed short-term effects of exposure to nature [8,11,55]. We carried out an observational study, with  
381 subjects in their residential environments, assessing a more general, and perhaps a more sustained relation  
382 between NOE and cognitive function.

383

384 While residential distance to NOE was related to cognitive function, other indicators of NOE showed no  
385 consistent association with cognition. We found no evidence for an association between surrounding  
386 greenness, as measured with the NDVI, and cognitive function. The NDVI is relatively easy to obtain and  
387 provides a useful measure of residential greenness relevant for studies of potential cognitive benefits of  
388 natural outdoor environments. However, it's a rather coarse measure of greenness that does not differentiate  
389 between size, type and function of greenness [56].

390

391 Furthermore, we did not find an association between engagement with NOE and cognitive function.  
392 Engagement with nature may not reach its full potential for cognitive benefits when people are distracted  
393 with other things while they are in the natural space (e.g. mobile phones, crowding). Another explanation  
394 may be that especially the larger natural spaces are of importance for cognitive function, since spaces of >1  
395 hectare were captured in the distance to natural outdoor environments indicator, while there was no such  
396 requirement in the other indicators. However, viewing nature from windows, which could include spaces

397 as small as a street trees, has been related to benefits for cognitive function [15,55], but we did not find  
398 such relations with our perceptions of NOE indicator which included window views. Lastly, another reason  
399 may be that the unintentional use of NOE, which was not captured in our measure of engagement with  
400 NOE, may be important for cognitive benefits, and may help explain our null findings.

401

402 We hypothesized that people living closer to nature feel less lonely, perceive higher social cohesion in their  
403 neighborhood, and have more contact with their neighbors, but could not find clear evidence for this. A  
404 Dutch study found that loneliness and shortage of social support mediated the relation between green space  
405 and health, but found no support for a mediating role of contact with neighbors [23]. They hypothesized  
406 that green spaces may be especially important for a sense of community through place attachment (i.e. the  
407 bond between individuals and places) and not because of actual contact with neighbors [23]. In a study  
408 about perceived greenness and mental health, social interaction with neighbors was not associated with  
409 mental health, while social cohesion was. It was postulated that more close social interaction than was  
410 assessed with their measure (e.g. waved, said hello, chatted) may be needed to confer health benefits [57].  
411 Another study found that urban gardening activities were beneficial for health through social involvement  
412 and neighborhood attachment [58]. If proximity to NOE does reduce loneliness and enhance social  
413 cohesion, it might support the hypothesis that this could partially mediate cognitive performance, as  
414 perceived social isolation has been identified as a risk factor for poorer overall cognitive performance, faster  
415 cognitive decline and poorer executive functioning [59]. The increase in cognitive load from worry and  
416 chronic surveillance for threat in the environment associated with social isolation may leave fewer cognitive  
417 resources to devote to completing the CTT, but the current results do not support this and further research  
418 is needed.

419

420 We could not establish mediation by physical activity, mental health, air pollution worries, or noise  
421 annoyance. Two previous studies reported mediation of the relation between green space and general health  
422 by social cohesion, but physical activity was less important [33,51]. One explanation could be that both  
423 here and in previous studies, the mediation of physical activity in general was investigated, rather than  
424 activity in natural outdoor environments, which may have distorted the relation. Furthermore, stress may  
425 be an important mediator, since it was found to play a large role in explaining the relation between green  
426 space and health [51], and may also be relevant for the relation with cognitive function. Unfortunately, no

427 data on stress were available in our sample. Another analysis of the Doetinchem PHENOTYPE data  
428 revealed that the perceived sound quality (i.e. soundscape) of people's favorite NOE could contribute to  
429 perceived restoration after visiting such a place [60].

430

431

432 No associations were found between any of the natural outdoor environment indicators and CTT errors.  
433 While completing the CTT as fast as possible is thought to be associated with visual attention, completing  
434 the CTT without errors is thought to be associated with impulse inhibition, another function related to  
435 executive functioning [61]. Our findings might indicate that contact with nature is more related to  
436 improvements in the visual attention functions, than with impulse inhibition. However, low variability of  
437 CTT errors in our data may also be the reason for our null findings. Future research could further investigate  
438 these and other aspects of cognitive function to establish what aspects of cognition may be relevant for  
439 effects of NOE.

440

441 Our study has several strengths and limitations. Strengths are the use of a variety of objective and validated  
442 instruments for exposure, mediators, and outcome assessments; and the investigation of different study  
443 populations from three European countries using the same methodology. Cognitive function was assessed  
444 with the CTT, which is regarded to be a language- and culture-free instrument. The use of such an  
445 instrument is important considering the international nature of our study. One of the limitations includes  
446 the relatively low response rates in our study, especially for Doetinchem. Non-response analysis for the  
447 Doetinchem sample showed that respondents had less often poor general health and rated NOE to be of  
448 higher importance for physical activity and relaxation compared to non-responders [35]. This might have  
449 affected the generalizability of our study. Another limitation is the missing data for the CTT, with more  
450 tests missing in Doetinchem and Stoke-on-Trent than in Barcelona, which resulted in unequal population  
451 sizes. The cognition test was taken after the questionnaire was completed, but if this exceeded one hour,  
452 the CTT was not taken. This may have resulted in potential bias by not having cognition test scores from  
453 those participants that took longer to complete the questionnaire. However, it is unlikely that this is  
454 associated with exposure to NOE and should not have introduced bias. We did observe that associations  
455 between residential distance to NOE and CTT completion time were only statistically significant for  
456 Barcelona, the city with the largest sample size, which may have driven the significant association in the

457 total sample. Another reason for this result might be that the smaller amount of NOE in Barcelona makes  
458 it easier to detect associations, and when there already is a certain amount of NOE, increasing levels of  
459 NOE have little additional value. Nonetheless, we must be cautious when interpreting these results  
460 considering the possibility that our observed associations were due to chance. Although efforts were made  
461 to take into account several covariates, estimates may have residual confounding by unknown factors that  
462 could vary between study areas. Finally, with our mediation analysis we assume a certain sequence of  
463 effects, while the cross-sectional nature of our study limits us to establish the directions of these effects.  
464 This is a general limitation of cross-sectional studies and underlines the need for longitudinal studies to  
465 gain knowledge on the potential causal link between NOE and cognition and its mechanisms [21].

466

## 467 **CONCLUSIONS**

468 In this cross-cultural study, we found an association between distance to NOE and CTT completion time,  
469 providing some indication that proximity to nature may benefit cognitive function, particularly visual  
470 attention. We observed no associations between other exposure indicators of NOE and cognitive function,  
471 nor could we establish mediation by physical activity, social interaction with neighbors, neighborhood  
472 social cohesion, loneliness, mental health, air pollution worries, or noise annoyance. When future research  
473 provides more evidence for an association between nature and cognition, and when more knowledge  
474 becomes available on what particular form of nature is beneficial to cognitive health and to whom, these  
475 findings could have implications for urban spatial planning policies targeted at improving access to nature  
476 in cities.

477

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