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Green space, air pollution, traffic noise and mental wellbeing throughout adolescence: Findings from the PIAMA study

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ABSTRACT

Background: Green space, air pollution and traffic noise exposure may be associated with mental health in adolescents. We assessed the associations of long-term exposure to residential green space, ambient air pollution and traffic noise with mental wellbeing from age 11 to 20 years.

Methods: We included 3059 participants of the Dutch PIAMA birth cohort who completed the five-item Mental Health Inventory (MHI-5) at ages 11, 14, 17 and/or 20 years. We estimated exposure to green space (the average Normalized Difference Vegetation Index (NDVI) and percentages of green space in circular buffers of 300 m, 1000 m and 3000 m), ambient air pollution (particulate matter (PM_{10} and $PM_{2.5}$), nitrogen dioxide, $PM_{2.5}$ absorbance and the oxidative potential of $PM_{2.5}$) and road traffic and railway noise (L_{den}) at the adolescents' home addresses at the times of completing the MHI-5. Associations with poor mental wellbeing (MHI-5 score ≤ 60) were assessed by generalized linear mixed models with a logit link, adjusting for covariates.

Results: The odds of poor mental wellbeing at age 11 to 20 years decreased with increasing exposure to green space in a 3000 m buffer (adjusted odds ratio (OR) 0.78 [95% CI 0.68–0.88] per IQR increase in the average NDVI; adjusted OR 0.77 [95% CI 0.67–0.88] per IQR increase in the total percentage of green space). These associations persisted after adjustment for air pollution and road traffic noise. Relationships between mental wellbeing and green space in buffers of 300 m and 1000 m were less consistent. Higher air pollution exposure was associated with higher odds of poor mental wellbeing, but these associations were strongly attenuated after adjustment for green space in a buffer of 3000 m, traffic noise and degree of urbanization. Traffic noise was not related to mental wellbeing throughout adolescence.

Conclusions: Residential exposure to green space may be associated with a better mental wellbeing in adolescents.

1. Introduction

It has been estimated that 10–20% of adolescents globally experience mental health problems (World Health Organization, 2020). Mental health conditions account for 16% of the global burden of disease and injury in persons aged 10 to 19 years (World Health Organization, 2020). Studies suggest that a substantial proportion of mental health conditions in adults originate in early life, which may indicate that poor mental wellbeing in childhood and adolescence could have long-lasting consequences (Kieling et al., 2011). It is therefore important to identify risk factors for poor mental wellbeing in adolescents. It is increasingly recognized that mental wellbeing is affected both by personal characteristics, such as genetic factors and lifestyle habits, and by environmental exposures (Helbich, 2018). Recent epidemiological studies have assessed associations of green space, air pollution or traffic noise with mental health outcomes in adults and children.

Multiple pathways have been proposed to explain the potential health benefits of green space (Hartig et al., 2014; Nieuwenhuijsen et al., 2017; Markevych et al., 2017). Green space may affect health directly, i.e., without individuals intentionally engaging with green space, by reducing stress and reducing exposure to environmental stressors (e.g., heat) (Hartig et al., 2014). Additionally, green spaces provide opportunities for physical activity and provide settings for contacts with neighbors, which are likely to increase social cohesion within a

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neighborhood (Hartig et al., 2014; Nieuwenhuijsen et al., 2017; Markevych et al., 2017). Two reviews have shown that exposure to green space may be beneficially associated with mental health outcomes in children and adolescents, including lower stress levels and fewer emotional and behavioral difficulties (McCormick, 2017; Vanaken and Danckaerts, 2018). In contrast, several studies did not find relationships between green space exposure and general mental wellbeing in adolescents (Srugo et al., 2019; Dzhambov et al., 2018; Saw et al., 2015). For example, neither residential proximity to green space nor the use of green spaces were related to the subjective wellbeing of students aged 18 to 25 years in Singapore (Saw et al., 2015). Comparisons across studies are, however, complicated by differences in study design, the different age groups and green space indicators studied, and differences in cultural, vegetative and climatic factors.

To our knowledge, no studies have examined associations of green space with self-reported mental wellbeing in children or adolescents in the Netherlands. Dutch residents generally do not need to travel over large distances for a walk in a green environment. For example, the average distance from a residential address to the nearest park or public garden in the Netherlands was approximately one kilometer in 2010 (Compendium voor de Leefomgeving. Afstand tot groen, 2010). It is likely that the health effects of green space differ across the world given the large differences in vegetative, cultural and climatic factors (Markevych et al., 2017). This indicates that studies in diverse geographic areas are needed.

Different biological mechanisms may explain potential relationships between air pollution and poor mental health, including inflammation, direct neurotoxicity and hormonal dysregulation (Buoli et al., 2018). A recent review has shown that exposure to increased concentrations of several air pollutants, including particulate matter, nitrogen dioxide (NO_2) and sulfur dioxide (SO_2), may be associated with poor mental health (Buoli et al., 2018). However, only few studies have assessed relationships between ambient air pollution and mental health outcomes in adolescents (Roberts et al., 2019; Oudin et al., 2016; Szyszkowicz et al., 2020; Reuben et al., 2021).

Traffic noise has been hypothesized to affect mental health through stress, annoyance and sleep disturbances (Münzel et al., 2018). A systematic review by Zare Sakhvidi et al. showed that data supporting the harmful effects of traffic noise on neurodevelopmental and mental health in children are heterogeneous and limited (Zare Sakhvidi et al., 2018). Similarly, two studies conducted in Bulgaria and the United States found no associations of noise exposure with self-reported mental health or mental health disorders in adolescents (Dzhambov et al., 2017; Rudolph et al., 2019).

In daily life, people are exposed to multiple environmental risks and amenities. Exposures to green space, air pollution and traffic noise are generally spatially correlated. Higher levels of green space are associated with lower levels of ambient air pollution and noise, while air pollution and noise share motorized road traffic as a major common source (Stansfeld, 2015; Fecht et al., 2016; Thiering et al., 2016; Bloemsma et al., 2019; Bloemsma et al., 2019). However, none of the epidemiological studies that have been performed so far has assessed the combined associations of these three environmental exposures with mental health in adolescents. The aim of this study is therefore to examine the associations of residential green space, air pollution and traffic noise with mental wellbeing from age 11 to 20 years.

2. Methods

2.1. Study design and population

This study was conducted within the ongoing Dutch Prevention and Incidence of Asthma and Mite Allergy (PIAMA) birth cohort study. The design of the PIAMA study has been described elsewhere (Brunekreef et al., 2002; Wijga et al., 2014). In brief, pregnant women were recruited in 1996/1997 from the general population in three different regions of the Netherlands during their second trimester of pregnancy. The baseline study population consisted of 3963 children. Data on sociodemographic and lifestyle characteristics, growth and development were collected through parental questionnaires during pregnancy, at the child's ages of three months and one year, and yearly thereafter until the child was eight years old. When the adolescents were 11, 14, and 17 years old, both parents and adolescents were requested to complete questionnaires. At age 20 years, only the adolescents themselves filled in a questionnaire. The study protocol has been approved by the institutional review boards of the participating institutes and written informed consent was obtained from all parents and children. In this study, we included 3059 adolescents (77.2% of the baseline study population) who have completed the five-item Mental Health Inventory (MHI-5) at least once at ages 11, 14, 17 or 20 years.

2.2. Mental wellbeing

At ages 11, 14, 17 and 20 years, participants of the PIAMA study were requested to complete the MHI-5 (Berwick et al., 1991; Rumpf et al., 2001). The MHI-5 is a validated brief questionnaire that has been widely used internationally to assess mental wellbeing and consists of the following five questions: "How much of the time, during the last month, have you 1) been a very nervous person?; 2) felt calm and peaceful?; 3) felt downhearted and blue?; 4) been a happy person?; and 5) felt so down in the dumps that nothing could cheer you up?" (Berwick et al., 1991). Response options ranged from 1 (constantly) to 5 (never). We calculated the MHI-5 score as follows: (the sum of the 5 items − 5) / 20 × 100. This resulted in scores ranging from 0 to 100, with higher scores indicating a better mental wellbeing. Adolescents with a MHI-5 score ≤ 60 were classified as adolescents with a poor mental wellbeing (Rumpf et al., 2001).

2.3. Residential exposures

We estimated green space, ambient air pollution and traffic noise levels at the adolescents' current home addresses at the times of completing the MHI-5 (i.e., recent exposures). Details of the exposure assessment have been published previously (Bloemsma et al., 2019; Bloemsma et al., 2019).

2.3.1. Green space

We used multiple indicators to assess residential exposure to green space. The Normalized Difference Vegetation Index (NDVI) was used to assess greenness levels around the adolescents' homes (Weier and Herring, 2000). The NDVI was derived from Landsat 5 Thematic Mapper data at 30 m × 30 m resolution. NDVI values range from −1 to 1, with higher values indicating a higher density of green vegetation. We created a map of the Netherlands by combining cloud free images of the summer of 2010. We calculated the average NDVI in circular buffers of 300 m, 1000 m and 3000 m around the adolescents' homes at the times of completing the MHI-5.

We additionally assessed the total percentage of green space and percentages of urban, agricultural and natural green space in buffers of 300 m, 1000 m and 3000 m around the adolescents' homes by using Bestand Bodemgebruik of 2006 and TOP10NL of 2016 (Centraal Bureau voor de Statistiek, 2008; Kadaster, 2017). Bestand Bodemgebruik and TOP10NL are detailed land-use maps of the Netherlands that, in contrast to the NVDI, do not include street greenery and private green property (such as gardens). Since TOP10NL is only available from 2012 onwards, we used Bestand Bodemgebruik to assess the percentages of green space when the study participants were 11 years old (around 2008/2009). TOP10NL of 2016 was used to determine the percentages of green space when the adolescents completed the MHI-5 at ages 14, 17 and 20 years. We assessed surrounding greenness and the percentages of green space in ArcGIS 10.2.2 (Esri, Redlands, CA, USA).

Even though most adolescents had any green space in a buffer of

300 m around their homes (between 84.9% and 99.9% in the different age categories; Table 1), a large proportion of the adolescents had no *natural* green space in a buffer of 300 m (between 57.0% and 83.3% in the different age categories). We therefore created a binary variable: natural green space in a buffer of 300 m yes/no.

2.3.2. Air pollution

We used land-use regression (LUR) models that were based on measurement campaigns performed in 2009 to estimate annual average concentrations of particulate matter with diameters of < 10 µm (PM_{10}) and < 2.5 µm ($PM_{2.5}$), NO_2, $PM_{2.5}$ absorbance (a marker of black carbon) and the oxidative potential of $PM_{2.5}$ (electron spin resonance (OP^{ESR}) and dithiothreitol (OP^{DTT})) at all ages without back-extrapolation. Detailed descriptions of the LUR model development have been published previously (Eeftens et al., 2012; Beelen et al., 2013; Yang et al., 2015). Substantial variability in annual average ambient air pollution concentrations was explained for PM_{10}, $PM_{2.5}$, NO_2, $PM_{2.5}$ absorbance and OP^{ESR} (leave-one-out cross validation (R^2_{LOOCV}) = 0.60–0.89) but not for OP^{DTT} (R^2_{LOOCV} = 0.47) (Eeftens et al., 2012; Beelen et al., 2013; Yang et al., 2015).

2.3.3. Traffic noise

We estimated annual average road traffic and railway noise levels at the adolescents' homes by the Standard Model Instrumentation for Noise Assessments (STAMINA). The STAMINA model has been developed by the Dutch National Institute for Public Health and the Environment and implements the standard Dutch Calculation method for traffic and industrial noise (Schreurs et al., 2010). The STAMINA model has been used to create noise maps covering the whole of the Netherlands, showing noise levels due to traffic and industrial noise. The extent of detail of the noise maps depends on the distance between the source and observation point: the highest resolution is 10x10m around noise sources. At increasing distances from the noise source, the resolution gradually decreases to at most 80x80m (Schreurs et al., 2010). Daily average (L_{den}) and nighttime average (L_{night}) traffic noise exposure was estimated for 2011. L_{den} is the A-weighted noise level over a 24 h period with a penalty of 5 dB(A) in the evening (7.00 pm−11.00 pm) and a penalty of 10 dB(A) at night (11.00 pm−7.00 am). Since L_{den} and L_{night} were highly correlated (r_s = 0.99 for road traffic noise; r_s = 0.96 for railway noise), we only included L_{den} in our analyses.

Table 1
Characteristics of the study population at ages 11, 14, 17 and 20 years and the distribution of green space, air pollution and traffic noise levels.

Characteristic	n (%) or median (25th−75th percentiles)			
	Age 11 years	Age 14 years	Age 17 years	Age 20 years
N	2624	2506	2085	2189
MHI-5 score	80.0 (75.0–85.0)	80.0 (70.0–85.0)	75.0 (65.0–85.0)	75.0 (65.0–85.0)
Poor mental wellbeing	154 (5.9)	302 (12.1)	384 (18.4)	518 (23.7)
Boys	1320 (50.3)	1258 (50.2)	1011 (48.5)	1037 (47.4)
Parental level of education				
Low/intermediate	1178 (45.2)	1107 (44.5)	872 (42.2)	957 (44.1)
High	1427 (54.8)	1379 (55.5)	1197 (57.9)	1211 (55.9)
Smoking in adolescent's home (yes)	333 (13.2)	241 (10.7)	155 (8.7)	194 (8.9)
Neighborhood SES [a]	0.36 (-0.25–0.96)	0.22 (-0.44–1.02)	0.24 (-0.51–0.96)	0.11 (-0.69–0.82)
Degree of urbanization				
Urban (≥1500 addresses/km^2)	1030 (40.1)	1028 (41.3)	884 (42.7)	1311 (61.7)
Non-urban (<1500 addresses/km^2)	1538 (59.9)	1463 (58.7)	1188 (57.3)	813 (38.3)
Season				
Winter	611 (23.6)	1220 (48.7)	905 (43.4)	1484 (67.9)
Spring	475 (18.4)	275 (11.0)	390 (18.7)	464 (21.2)
Summer	533 (20.6)	191 (7.6)	38 (1.8)	189 (8.6)
Fall	968 (37.4)	818 (32.7)	752 (36.1)	50 (2.3)
Average NDVI in 300 m	0.55 (0.48–0.61)	0.55 (0.48–0.61)	0.55 (0.48–0.61)	0.50 (0.42–0.58)
Total percentage of green space in 300 m	12.2 (2.4–29.1)	19.7 (11.6–33.2)	19.7 (11.6–33.4)	15.1 (7.3–27.2)
Any green space within 300 m	2190 (84.9)	2498 (99.9)	2076 (99.9)	2048 (98.9)
Percentage urban green in 300 m	0.7 (0.0–7.8)	9.8 (4.4–15.7)	9.6 (4.3–15.5)	8.6 (3.8–14.6)
Percentage agricultural green in 300 m	0.0 (0.0–19.7)	1.1 (0.0–16.2)	1.1 (0.0–17.0)	0.0 (0.0–9.1)
Percentage natural green in 300 m	0.0 (0.0–0.0)	0.0 (0.0–1.3)	0.0 (0.0–1.3)	0.0 (0.0–0.3)
Any natural green within 300 m	428 (16.7)	1059 (42.5)	890 (43.0)	636 (30.7)
Average NDVI in 1000 m	0.58 (0.51–0.65)	0.58 (0.51–0.65)	0.58 (0.51–0.65)	0.53 (0.45–0.61)
Total percentage of green space in 1000 m	31.3 (15.5–52.6)	35.4 (23.1–52.4)	35.9 (23.2–52.5)	26.5 (14.6–44.8)
Percentage urban green in 1000 m	3.8 (1.3–7.5)	9.3 (5.1–13.9)	9.1 (5.1–13.7)	9.6 (5.8–14.0)
Percentage agricultural green in 1000 m	20.3 (3.8–43.3)	18.5 (4.7–40.0)	19.0 (5.0–40.5)	8.7 (0.1–28.4)
Percentage natural green in 1000 m	0.5 (0.0–4.6)	1.8 (0.3–6.0)	1.8 (0.3–5.8)	0.8 (0.0–3.7)
Average NDVI in 3000 m	0.63 (0.55–0.68)	0.62 (0.56–0.68)	0.62 (0.55–0.68)	0.57 (0.50–0.66)
Total percentage of green space in 3000 m	55.3 (39.4–70.2)	56.3 (42.8–67.0)	56.2 (42.6–66.9)	44.5 (29.7–60.3)
Percentage urban green in 3000 m	2.8 (1.0–5.0)	6.0 (2.7–9.6)	5.9 (2.8–9.6)	8.3 (4.1–12.1)
Percentage agricultural green in 3000 m	43.0 (24.9–61.5)	40.4 (23.6–55.7)	40.2 (23.8–55.8)	27.4 (12.3–48.7)
Percentage natural green in 3000 m	3.5 (1.4–10.5)	4.1 (2.1–10.3)	4.1 (2.1–10.0)	3.1 (1.8–6.5)
PM_{10} (µg/m^3) [b]	24.5 (24.0–25.0)	24.5 (24.0–25.0)	24.5 (24.0–25.0)	24.9 (24.2–25.7)
$PM_{2.5}$ (µg/m^3) [b]	16.5 (15.6–16.7)	16.5 (15.6–16.7)	16.5 (15.6–16.7)	16.5 (15.8–16.8)
OP^{ESR} (A.U./m^3) [b]	934.3 (774.7–1020.8)	930.3 (776.1–1017.7)	930.6 (776.5–1016.2)	955.1 (844.6–1049.9)
OP^{DTT} (nmol DTT/min/m^3) [b]	1.1 (1.0–1.3)	1.1 (1.0–1.2)	1.1 (1.0–1.2)	1.2 (1.1–1.3)
NO_2 (µg/m^3) [b]	22.8 (17.9–27.0)	22.7 (17.7–26.9)	22.7 (17.8–27.0)	25.0 (20.7–29.6)
$PM_{2.5}$ absorbance (10^{-5}/m) [b]	1.2 (1.0–1.3)	1.2 (1.0–1.3)	1.2 (1.0–1.3)	1.3 (1.1–1.4)
Road traffic noise (L_{den} dB(A)) [c]	52.5 (49.4–56.3)	52.4 (49.4–56.3)	52.4 (49.3–56.5)	54.4 (50.4–58.9)
Railway noise (L_{den} dB(A)) [c]	30.4 (29.0–37.8)	30.3 (29.0–37.7)	30.9 (29.0–38.0)	32.6 (29.0–39.3)

Abbreviations: SES = socioeconomic status; NDVI = Normalized Difference Vegetation Index; OP^{ESR} = electron spin resonance; OP^{DTT} = dithiothreitol.

[a] A higher score indicates a higher SES.

[b] Air pollution is modeled based upon 2009 measurements for all age categories.

[c] Daily average traffic noise exposure was estimated for 2011 and used for all age categories.

2.4. Covariates

We included the following set of *a priori* selected covariates in our analyses: age, sex, parental level of education, any smoking in the adolescent's home, season (winter, spring, summer and fall) and neighborhood socioeconomic status (SES). Parental level of education as an indicator of family SES (defined as the maximum of the mother's and father's educational level and categorized as low/intermediate and high) was obtained from a parental questionnaire administered when the children were one year old. In addition, we included any smoking in the adolescent's home as a covariate, because we consider this variable as an indicator of family lifestyle and home environment that may be relevant in addition to parental education. We assessed any smoking in the adolescent's home (at least once a week vs. no) through parental questionnaires from age 11 to 17 years. At age 20 years, study participants reported exposure to secondhand smoke at home themselves. We used the status scores of the 4-digit postal code areas from the Netherlands Institute for Social Research (SCP) of 2006 to 2017 to determine neighborhood SES. Status scores comprise the average income, the percentage unemployed persons, percentage of residents with a low income and the percentage of low educated residents in a postal code area. A higher status score indicates a higher neighborhood SES (Knol, 2012).

2.5. Statistical methods

We assessed pairwise Spearman correlations between the green space indicators, ambient air pollutants and traffic noise. We examined the shapes of the unadjusted associations of the continuous exposures and covariates with mental wellbeing by generalized additive models with integrated smoothness estimation and a logit link (GAM function; The R Project for Statistical Computing 2.8.0, https://www.r-project.org). Since there was no evidence of non-linearity (Fig. S1), we included all exposures as continuous variables in the analyses (except for natural green space in a buffer of 300 m) and expressed associations per interquartile range increase (IQR) in exposure. We examined the overall associations of green space, air pollution and traffic noise with poor mental wellbeing from age 11 to 20 years with generalized linear mixed models with a logit link. We included random subject-specific intercepts to account for within-subject correlation across the repeated mental wellbeing measurements. Additionally, age-specific estimates were obtained by including exposure-age interaction terms. Since the percentage of missing values per exposure or covariate was low, we have not imputed missing values. We have decided not to examine associations of the exposures at specific ages with mental wellbeing at the following age, because we hypothesized that current rather than past exposure to green space (by decreasing stress and/or by increasing physical activity levels and social cohesion) and traffic noise (through stress, annoyance and sleep disturbances) may be associated with mental wellbeing. Additionally, exposure to residential green space, air pollution and traffic noise hardly changed from age 11 to 17 years, so we were unable to study changes in mental wellbeing in relation to changes in the exposures.

We defined *a priori* three regression models with increasing degree of covariate adjustment. Model 1 was adjusted for age. Model 2 was adjusted for age, sex, parental level of education, any smoking in the adolescent's home and season. Model 3 further included neighborhood SES. To assess the independent associations of the different types of green space, we always adjusted associations with the percentages of urban, agricultural and natural green space for the other two types of green space in the same buffer size. We evaluated effect modification by sex and parental level of education (low/intermediate vs. high) by adding product interaction terms for exposure-sex or exposure-parental level of education to the adjusted models (model 3) and by presenting results stratified by sex and parental educational level. Finally, we examined potential confounding of associations with one exposure by the other exposures of interest with multi-exposure models (i.e., models including green space, air pollution and traffic noise).

People living in urban areas may have a poorer mental wellbeing than people living in less urbanized areas (Gruebner et al., 2017; Okkels et al., 2018). However, adjusting for degree of urbanization could lead to over-adjustment in this study, since the degree of urbanization is related to sources of residential green space, air pollution and traffic noise levels. As a sensitivity analysis, we have therefore additionally adjusted the multi-exposure models for degree of urbanization. The degree of urbanization was assessed by the average number of addresses per km^2 of the 4-digit postal code areas, provided by Statistics Netherlands (CBS). CBS divides the degree of urbanization of 4-digit postal code areas into five categories and labels the highest two categories, with an average of ≥ 1500 addresses/km^2, as strongly urbanized or extremely urbanized. We dichotomized the degree of urbanization as follows: urban area ($\geq$1500 addresses/km^2) and non-urban area ($<$1500 addresses/km^2). Furthermore, we also estimated associations of the average NDVI and total percentage of green space with poor mental wellbeing in adolescents who have lived in an urban area throughout the study period ($n = 1121$).

Finally, as a sensitivity analysis, we examined associations of green space, air pollution and traffic noise with continuous MHI-5 scores from age 11 to 20 years. The statistical analyses were performed using SAS version 9.4 (SAS Institute Inc., Cary, NC, USA), except the analyses of the linearity of the associations, which were performed with R version 3.4.3 (R Core Team, 2020).

3. Results

Characteristics of the study population and the distributions of residential green space, air pollution and traffic noise levels are shown in Table 1. Study participants more often lived in an urban area, had lower levels of residential green space and were exposed to higher levels of ambient air pollution (except for $PM_{2.5}$) and traffic noise at age 20 than at ages 11, 14 and 17 years. The prevalence of poor mental wellbeing increased from 5.9% at age 11 to 23.7% at age 20 years (Table 1). 1567 participants (51.2%) have completed the MHI-5 at all four timepoints, i.e., at ages 11, 14, 17 and 20 years. Of these, 987 participants (63.0%) had a good mental wellbeing at all ages, while 7 participants (0.4%) had a poor mental wellbeing throughout adolescence.

Spearman correlations between the green space indicators and estimated concentrations of ambient air pollutants and traffic noise were negative, except for the correlations with urban green space (Fig. S2). Road traffic noise levels were moderately positively correlated with the various air pollutants ($r_s = 0.30$ to 0.51). Correlations between ambient air pollution and the number of addresses per km^2 (as an indicator of the degree of urbanization) ranged from 0.45 to 0.74 (Table S1). The number of addresses per km^2 was negatively correlated with the green space indicators, except for urban green in buffers of 300 m ($r_s = 0.25$), 1000 m ($r_s = 0.54$) and 3000 m ($r_s = 0.75$).

In single-exposure models, we observed lower odds of poor mental wellbeing from age 11 to 20 years with higher average NDVI in a buffer of 300 m (odds ratio (OR) 0.88 [95% confidence interval (CI) 0.78–0.99] per 0.13 increase in the average NDVI in model 3, Table 2). The odds of poor mental wellbeing throughout adolescence was also lower with higher average NDVI and total percentage of green space in buffers of 1000 m and 3000 m (for example, OR 0.78 [95% CI 0.68–0.88] per 0.14 increase in the average NDVI in 3000 m and OR 0.77 [95% CI 0.67–0.88] per 28.3% increase in the total percentage of green space in 3000 m in model 3). When accounting for type of green, associations with a buffer of 3000 m were found for agricultural and natural green space, but not for urban green space. Higher exposure to ambient air pollution was associated with higher odds of poor mental wellbeing from age 11 to 20 years (for example, OR 1.23 [95% CI 1.08–1.40] per 0.28 nmol DTT/min/m^3 increase in OP^{DTT} and OR 1.23 [95% CI 1.09–1.38] per 9.11 μg/m^3 increase in NO_2 in model 3). We found no

Table 2
Associations of green space, air pollution and traffic noise with poor mental wellbeing from age 11 to 20 years from single-exposure models.

Exposure (increment)	Model 1[a]	Model 2[b]	Model 3[c]
	OR (95% CI)	OR (95% CI)	OR (95% CI)
Average NDVI in 300 m (0.13)	0.87 (0.78–0.97)	0.87 (0.78–0.97)	0.88 (0.78–0.99)
Total percentage of green space in 300 m (23.01)	0.96 (0.86–1.06)	0.97 (0.87–1.07)	0.97 (0.87–1.07)
Urban green in 300 m (11.84)	1.10 (0.97–1.25)	1.12 (0.99–1.27)	1.11 (0.98–1.26)
Agricultural green in 300 m (15.54)	0.98 (0.90–1.06)	0.99 (0.91–1.08)	0.98 (0.90–1.07)
Natural green in 300 m (yes vs. no)	0.94 (0.77–1.15)	0.91 (0.74–1.12)	0.93 (0.76–1.15)
Average NDVI in 1000 m (0.14)	0.82 (0.73–0.92)	0.81 (0.72–0.92)	0.83 (0.73–0.94)
Total percentage of green space in 1000 m (31.69)	0.84 (0.74–0.95)	0.83 (0.73–0.95)	0.84 (0.73–0.96)
Urban green in 1000 m (8.99)	1.03 (0.89–1.20)	1.03 (0.88–1.21)	1.02 (0.87–1.20)
Agricultural green in 1000 m (36.61)	0.85 (0.72–1.01)	0.86 (0.72–1.02)	0.86 (0.72–1.03)
Natural green in 1000 m (5.10)	0.97 (0.91–1.03)	0.95 (0.89–1.02)	0.95 (0.89–1.02)
Average NDVI in 3000 m (0.14)	0.75 (0.66–0.85)	0.76 (0.67–0.86)	0.78 (0.68–0.88)
Total percentage of green space in 3000 m (28.34)	0.75 (0.66–0.86)	0.76 (0.67–0.87)	0.77 (0.67–0.88)
Urban green in 3000 m (7.16)	0.95 (0.75–1.19)	0.96 (0.75–1.21)	0.95 (0.75–1.21)
Agricultural green in 3000 m (35.14)	0.72 (0.57–0.92)	0.74 (0.58–0.94)	0.74 (0.58–0.94)
Natural green in 3000 m (7.52)	0.91 (0.85–0.99)	0.91 (0.84–0.99)	0.92 (0.85–1.00)
PM_{10} (1.15 μg/m^3)	1.14 (1.05–1.25)	1.07 (0.98–1.17)	1.07 (0.98–1.17)
$PM_{2.5}$ (1.15 μg/m^3)	1.15 (1.00–1.32)	1.15 (1.00–1.33)	1.19 (1.03–1.38)
OP^{ESR} (241.89 A.U./m^3)	1.09 (0.96–1.23)	1.08 (0.95–1.23)	1.10 (0.96–1.25)
OP^{DTT} (0.28 nmol DTT/min/m^3)	1.19 (1.05–1.35)	1.23 (1.08–1.40)	1.23 (1.08–1.40)
NO_2 (9.11 μg/m^3)	1.21 (1.08–1.36)	1.21 (1.08–1.36)	1.23 (1.09–1.38)
$PM_{2.5}$ absorbance (0.29 × 10^{-5}/m)	1.18 (1.07–1.30)	1.17 (1.06–1.29)	1.19 (1.07–1.31)
Road traffic noise (7.40 dB(A))	1.05 (0.94–1.16)	1.03 (0.92–1.15)	1.04 (0.94–1.17)
Railway noise (9.20 dB(A))	1.03 (0.92–1.14)	1.03 (0.92–1.15)	1.03 (0.93–1.16)

Abbreviations: OR = odds ratio; CI = confidence interval; NDVI = Normalized Difference Vegetation Index; OP^{ESR} = electron spin resonance; OP^{DTT} = dithiothreitol.
Associations are shown for an interquartile range increase in exposure, except for natural green in a buffer of 300 m.
Associations with the percentages of urban, agricultural and natural green space are adjusted for the other two types of green space in the same buffer size (plus additional confounders as detailed in footnotes a-c).
[a] Adjusted for age.
[b] Adjusted for age, sex, parental level of education, any smoking in the adolescent's home and season.
[c] Includes model 2 and neighborhood SES.

relationships between traffic noise and poor mental wellbeing (Table 2).

We did not observe significant interactions between sex or parental level of education and the exposures (all p-values for interaction ≥ 0.09). However, associations of green space and most ambient air pollutants with mental wellbeing were stronger in girls and adolescents with a low/intermediate parental level of education compared to boys and adolescents with a high parental level of education (Tables S2 and S3).

Table 3 shows the age-specific associations of green space, air pollution and traffic noise with poor mental wellbeing in adolescence.

Table 3
Age-specific associations of green space, air pollution and traffic noise with poor mental wellbeing from age 11 to 20 years. [a].

Exposure (increment)	Age 11 years	Age 14 years	Age 17 years	Age 20 years
	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)
Average NDVI in 300 m (0.13)	0.78 (0.59–1.04)	0.88 (0.70–1.10)	0.92 (0.74–1.14)	0.89 (0.76–1.04)
Total percentage of green space in 300 m (23.01)	0.86 (0.69–1.06)	1.01 (0.84–1.23)	1.05 (0.86–1.28)	0.95 (0.80–1.13)
Urban green in 300 m (11.84)	1.20 (0.89–1.62)	1.16 (0.91–1.47)	1.16 (0.92–1.47)	1.06 (0.87–1.30)
Agricultural green in 300 m (15.54)	0.90 (0.77–1.06)	1.02 (0.87–1.20)	1.06 (0.90–1.25)	0.98 (0.84–1.14)
Natural green in 300 m (yes vs. no)	0.60 (0.32–1.12)	0.96 (0.67–1.38)	0.91 (0.63–1.31)	0.97 (0.69–1.37)
Average NDVI in 1000 m (0.14)	0.75 (0.57–1.00)	0.76 (0.60–0.96)	0.89 (0.71–1.12)	0.85 (0.72–1.01)
Total percentage of green space in 1000 m (31.69)	0.80 (0.61–1.04)	0.83 (0.65–1.06)	0.92 (0.72–1.17)	0.83 (0.67–1.03)
Urban green in 1000 m (8.99)	1.17 (0.82–1.67)	0.98 (0.72–1.35)	1.00 (0.74–1.37)	1.03 (0.82–1.31)
Agricultural green in 1000 m (36.61)	0.83 (0.60–1.16)	0.85 (0.60–1.21)	0.90 (0.64–1.28)	0.87 (0.66–1.15)
Natural green in 1000 m (5.10)	0.94 (0.81–1.08)	0.94 (0.83–1.06)	1.00 (0.90–1.12)	0.92 (0.81–1.05)
Average NDVI in 3000 m (0.14)	0.73 (0.55–0.96)	0.70 (0.56–0.89)	0.78 (0.62–0.98)	0.83 (0.69–1.00)
Total percentage of green space in 3000 m (28.34)	0.73 (0.56–0.95)	0.71 (0.56–0.92)	0.79 (0.62–1.01)	0.81 (0.67–0.99)
Urban green in 3000 m (7.16)	0.82 (0.43–1.56)	0.83 (0.54–1.27)	0.85 (0.55–1.30)	1.20 (0.83–1.73)
Agricultural green in 3000 m (35.14)	0.63 (0.39–1.01)	0.62 (0.39–0.98)	0.69 (0.44–1.10)	0.96 (0.66–1.39)
Natural green in 3000 m (7.52)	0.93 (0.79–1.08)	0.88 (0.76–1.02)	0.91 (0.79–1.04)	0.94 (0.82–1.07)
PM_{10} (1.15 μg/m^3)	1.10 (0.88–1.36)	1.13 (0.95–1.34)	1.07 (0.90–1.28)	1.14 (1.02–1.28)
$PM_{2.5}$ (1.15 μg/m^3)	1.06 (0.76–1.48)	1.09 (0.83–1.44)	1.34 (1.02–1.76)	1.22 (1.01–1.47)
OP^{ESR} (241.89 A.U./m^3)	1.03 (0.76–1.40)	1.02 (0.79–1.31)	1.33 (1.04–1.70)	1.06 (0.89–1.26)
OP^{DTT} (0.28 nmol DTT/min/m^3)	1.26 (0.94–1.67)	1.17 (0.93–1.47)	1.18 (0.94–1.48)	1.29 (1.06–1.57)
NO_2 (9.11 μg/m^3)	1.16 (0.89–1.52)	1.27 (1.02–1.58)	1.25 (1.00–1.55)	1.22 (1.03–1.43)
$PM_{2.5}$ absorbance (0.29 × 10^{-5}/m)	1.13 (0.89–1.43)	1.17 (0.96–1.43)	1.22 (1.01–1.48)	1.19 (1.05–1.36)
Road traffic noise (7.40 dB(A))	0.88 (0.67–1.16)	0.93 (0.75–1.16)	1.14 (0.93–1.41)	1.10 (0.94–1.28)
Railway noise (9.20 dB(A))	0.83 (0.63–1.09)	1.00 (0.82–1.23)	1.15 (0.95–1.40)	1.06 (0.90–1.24)

Abbreviations: OR = odds ratio; CI = confidence interval; NDVI = Normalized Difference Vegetation Index.
Associations are shown for an interquartile range increase in exposure, except for natural green in a buffer of 300 m.
[a] Adjusted for age, sex, parental level of education, any smoking in the adolescent's home, season and neighborhood SES. Associations with the percentages of urban, agricultural and natural green space are additionally adjusted for the other two types of green space.

Relationships of the average NDVI and total percentage of green space in a buffer of 3000 m with lower odds of poor mental wellbeing were consistent across all ages. Associations between the air pollutants and poor mental wellbeing were positive at all ages and generally strongest at ages 17 and 20 years.

Results from three-exposure models are presented in Table 4. We did

Table 4
Associations of green space, air pollution and road traffic noise with poor mental wellbeing from age 11 to 20 years from three-exposure models.

Model [a]	Exposure	Green space in 300 m	Green space in 1000 m	Green space in 3000 m
		OR (95% CI)	OR (95% CI)	OR (95% CI)
PM_{10} + NDVI + road traffic noise	PM_{10}	1.09 (0.98–1.21)	1.07 (0.95–1.19)	1.04 (0.92–1.17)
	NDVI	0.89 (0.79–1.01)	0.84 (0.73–0.97)	0.78 (0.67–0.91)
	Road traffic noise	0.94 (0.82–1.07)	0.93 (0.82–1.06)	0.95 (0.83–1.08)
PM_{10} + total green space + road traffic noise	PM_{10}	1.09 (0.98–1.21)	1.07 (0.95–1.19)	1.00 (0.89–1.14)
	Total green space	0.98 (0.88–1.10)	0.86 (0.74–1.00)	0.76 (0.64–0.90)
	Road traffic noise	0.96 (0.84–1.10)	0.94 (0.83–1.08)	0.96 (0.84–1.09)
$PM_{2.5}$ + NDVI + road traffic noise	$PM_{2.5}$	1.12 (0.95–1.32)	1.10 (0.94–1.31)	1.09 (0.92–1.29)
	NDVI	0.88 (0.78–0.99)	0.82 (0.72–0.94)	0.77 (0.67–0.88)
	Road traffic noise	0.95 (0.83–1.08)	0.93 (0.82–1.06)	0.93 (0.82–1.06)
$PM_{2.5}$ + total green space + road traffic noise	$PM_{2.5}$	1.21 (1.03–1.43)	1.08 (0.91–1.28)	1.05 (0.89–1.25)
	Total green space	1.00 (0.89–1.11)	0.85 (0.73–0.98)	0.76 (0.66–0.89)
	Road traffic noise	0.97 (0.86–1.11)	0.95 (0.84–1.08)	0.94 (0.83–1.07)
OP^{ESR} + NDVI + road traffic noise	OP^{ESR}	1.06 (0.92–1.23)	1.05 (0.90–1.21)	1.04 (0.90–1.20)
	NDVI	0.89 (0.79–1.01)	0.83 (0.73–0.95)	0.77 (0.67–0.88)
	Road traffic noise	0.98 (0.86–1.11)	0.97 (0.85–1.10)	0.95 (0.84–1.08)
OP^{ESR} + total green space + road traffic noise	OP^{ESR}	1.09 (0.94–1.26)	1.04 (0.90–1.22)	1.00 (0.85–1.16)
	Total green space	0.99 (0.88–1.11)	0.85 (0.73–0.99)	0.76 (0.66–0.88)
	Road traffic noise	1.01 (0.89–1.14)	0.98 (0.87–1.12)	0.97 (0.86–1.10)
OP^{DTT} + NDVI + road traffic noise	OP^{DTT}	1.23 (1.03–1.47)	1.15 (0.97–1.37)	1.09 (0.93–1.28)
	NDVI	0.99 (0.85–1.16)	0.90 (0.76–1.06)	0.79 (0.68–0.93)
	Road traffic noise	0.98 (0.87–1.11)	0.97 (0.86–1.09)	0.95 (0.85–1.07)
OP^{DTT} + total green space + road traffic noise	OP^{DTT}	1.32 (1.12–1.56)	1.20 (1.01–1.43)	1.11 (0.94–1.32)
	Total green space	1.11 (0.97–1.27)	0.95 (0.79–1.14)	0.81 (0.68–0.97)
	Road traffic noise	1.00 (0.89–1.12)	0.98 (0.87–1.11)	0.96 (0.85–1.08)
NO_2 + NDVI + road traffic noise	NO_2	1.27 (1.08–1.49)	1.21 (1.02–1.43)	1.12 (0.94–1.33)
	NDVI	0.99 (0.86–1.14)	0.92 (0.78–1.09)	0.81 (0.69–0.97)
	Road traffic noise	0.94 (0.82–1.06)	0.94 (0.83–1.06)	0.93 (0.82–1.06)
NO_2 + total green space + road traffic noise	NO_2	1.31 (1.13–1.53)	1.25 (1.06–1.49)	1.12 (0.92–1.36)
	Total green space	1.08 (0.95–1.22)	0.98 (0.82–1.17)	0.83 (0.68–1.02)
	Road traffic noise	0.94 (0.83–1.07)	0.94 (0.83–1.07)	0.95 (0.84–1.07)
$PM_{2.5}$ absorbance + NDVI + road traffic noise	$PM_{2.5}$ absorbance	1.22 (1.07–1.39)	1.19 (1.04–1.36)	1.14 (0.99–1.31)
	NDVI	0.95 (0.83–1.08)	0.89 (0.77–1.03)	0.82 (0.70–0.95)
	Road traffic noise	0.91 (0.79–1.04)	0.91 (0.79–1.04)	0.90 (0.79–1.03)
$PM_{2.5}$ absorbance + total green space + road traffic noise	$PM_{2.5}$ absorbance	1.25 (1.10–1.42)	1.20 (1.05–1.38)	1.12 (0.97–1.31)
	Total green space	1.03 (0.92–1.16)	0.93 (0.79–1.09)	0.83 (0.69–0.98)
	Road traffic noise	0.92 (0.81–1.05)	0.91 (0.80–1.04)	0.93 (0.81–1.06)

Abbreviations: OR = odds ratio; CI = confidence interval; NDVI = Normalized Difference Vegetation Index; OP^{ESR} = electron spin resonance; OP^{DTT} = dithiothreitol. Associations are shown for an interquartile range increase in exposure.

[a] Additionally adjusted for age, sex, parental level of education, any smoking in the adolescent's home, season and neighborhood SES.

not find evidence of multicollinearity in the three-exposure models (all variance inflation factors < 2.8). After additional adjustment for ambient air pollution and road traffic noise, associations with the average NDVI and total percentage of green space in a buffer of 3000 m persisted (for example, OR 0.79 [95% CI 0.68–0.93] per 0.14 increase in the average NDVI and OR 0.81 [95% CI 0.68–0.97] per 28.3% increase in the total percentage of green space after adjustment for OP^{DTT} and road traffic noise). In contrast, relationships with the average NDVI in a buffer of 300 m weakened in three-exposure models with air pollution and traffic noise. Finally, associations of the average NDVI and total percentage of green space in a buffer of 1000 m with lower odds of poor mental wellbeing persisted in models including PM_{10}, $PM_{2.5}$ or OP^{ESR}, but weakened in models including OP^{DTT}, NO_2 or $PM_{2.5}$ absorbance (Table 4).

Associations of OP^{DTT}, NO_2 and $PM_{2.5}$ absorbance with higher odds of poor mental wellbeing from age 11 to 20 years remained after adjustment for green space in a buffer of 300 m or 1000 m and road traffic noise (Table 4). Relationships with the air pollutants were, however, strongly attenuated in three-exposure models with green space in a buffer of 3000 m. Associations were still positive and strongest for NO_2 and $PM_{2.5}$ absorbance (OR 1.12 [95% CI 0.94–1.33] per 9.11 $\mu g/m^3$ increase in NO_2 and OR 1.14 [95% CI 0.99–1.31] per 0.29×10^{-5}/m increase in $PM_{2.5}$ absorbance after adjustment for the average NDVI in 3000 m and road traffic noise).

Adolescents living in urban areas ($\geq$1500 addresses/km^2) had higher odds of poor mental wellbeing than adolescents living in non-urban areas (OR 1.38 [95% CI 1.16–1.64]). Associations of the average NDVI in a buffer of 3000 m with lower odds of poor mental wellbeing remained after additional adjustment for degree of urbanization (Table S4). Relationships with the air pollutants and the total percentage of green space in a buffer of 3000 m slightly attenuated after adjustment for degree of urbanization.

In adolescents living in an urban area, green space in a buffer of 1000 m was not related to mental wellbeing from age 11 to 20 years (Table S5; OR 0.95 [95% CI 0.75–1.20] per 0.14 increase in the average NDVI and OR 0.92 [95% CI 0.65–1.31] per 31.7% increase in the total percentage of green space). In this subgroup, we did observe associations of the average NDVI and total percentage of green space in a buffer of 3000 m with lower odds of poor mental wellbeing. Due to the smaller sample size, however, confidence intervals widened (OR 0.83 [95% CI 0.66–1.04] per 0.14 increase in the average NDVI and OR 0.77 [95% CI 0.58–1.03] per 28.3% increase in the total percentage of green space).

Finally, the average NDVI and total percentage of green space in all buffer sizes were associated with higher MHI-5 scores throughout adolescence (Table S6), which is consistent with the results of the main analyses. All ambient air pollutants were related to lower MHI-5 scores, while we observed no associations with traffic noise.

4. Discussion

4.1. Main findings

We found that the odds of poor mental wellbeing from age 11 to 20 years was lower with higher average NDVI and total percentage of green space in a buffer of 3000 m. These associations were consistent across all ages and remained after adjustment for air pollution, traffic noise and degree of urbanization. Relationships between green space in buffers of 300 m and 1000 m and mental wellbeing were less consistent. Higher ambient air pollution concentrations were associated with higher odds of poor mental wellbeing throughout adolescence, but these associations weakened after adjustment for green space in a buffer of 3000 m, traffic noise and degree of urbanization. Traffic noise was not associated with mental wellbeing in adolescents.

4.2. Comparison with previous studies and interpretation of findings

We have previously shown that residential green space in a buffer of 3000 m was associated with a larger diurnal decrease in saliva cortisol levels, which may indicate lower chronic stress levels, at age 12 years in the PIAMA birth cohort study (Bloemsma et al., 2021). However, to our knowledge, this is the first study that has examined relationships between green space and self-reported mental wellbeing in adolescents in the Netherlands.

Our findings are in line with two reviews that showed that exposure to green space may be beneficially associated with mental health outcomes in children and adolescents (McCormick, 2017; Vanaken and Danckaerts, 2018). However, three previous studies did not find relationships between green space exposure and subjective general mental health in adolescents (Srugo et al., 2019; Dzhambov et al., 2018; Saw et al., 2015). Dzhambov et al. found no associations between self-reported mental wellbeing and the average NDVI, Soil Adjusted Vegetation Index and tree cover density in a buffer of 500 m surrounding the homes of 399 adolescents in Bulgaria (Dzhambov et al., 2018). This is consistent with our finding of no association between green space in a buffer of 300 m and mental wellbeing in adolescence, after adjustment for ambient air pollution and road traffic noise. We did not include green space in buffers of 500 m surrounding the adolescents' homes in this study, because green space indicators in buffers of 300 m and 500 m were highly correlated. Associations with mental wellbeing are therefore likely similar for green space in buffers of 300 m and 500 m in our study. Another study found no associations between the average NDVI in buffers of 500 m and 1000 m surrounding the schools of 6313 students aged 11–20 years in Canada with self-rated mental health (Srugo et al., 2019). Finally, in a study by Saw et al., neither residential proximity to green space (defined as the accessibility to nature reserves, regional parks, neighborhood parks and park connectors) nor the use of green spaces were related to the subjective wellbeing of 426 students aged 18 to 25 years in Singapore (Saw et al., 2015). Comparisons across studies are, however, complicated by the inclusion of different types of green space (e.g., residential green space in the present study and school greenness in the study from Canada), different buffer sizes and cultural and climatic differences.

We found associations of green space in a buffer of 3000 m with better mental wellbeing in adolescents, which were consistent over a period of nearly ten years. Associations with green space in buffers of 300 m and 1000 m were less consistent. This may imply that the availability of green space in a greater area surrounding the adolescents' homes, rather than green space closer to home, is related to a better mental wellbeing in our study population. Green space may improve mental wellbeing by increasing physical activity levels and social cohesion and by reducing stress and exposure to environmental stressors (such as air pollution, traffic noise and heat) (Hartig et al., 2014; Nieuwenhuijsen et al., 2017; Markevych et al., 2017). We explored the possibility of performing model-based causal mediation analyses to assess the mediation of the associations between green space and mental wellbeing by ambient air pollution and traffic noise levels. We used the mediation package in R (version 3.4.3) with logistic mixed effects models with random subject intercepts for the outcome models and linear mixed effects models for the mediator models. Due to problems with model convergence, we were not able to get valid results and did not include these mediation analyses in our manuscript. We have previously shown that green space in a buffer of 3000 m may be associated with lower stress levels at age 12 years in the PIAMA study (Bloemsma et al., 2021), but we were unable to include biomarkers of stress in the present study. Future studies are needed that explore the pathways through which green space may impact mental wellbeing of adolescents.

In this study, adolescents living in urban areas (≥1500 addresses/km^2) had higher odds of poor mental wellbeing than adolescents living in non-urban areas. Associations of green space in a buffer of 3000 m with a better mental wellbeing remained after adjustment for degree of urbanization. Moreover, we also observed these relationships in the subgroup of adolescents who lived in an urban area. It is, however, possible that our observed associations partly reflect urban–rural differences in mental wellbeing (for reasons other than air pollution, traffic noise or lack of green space), which we did not adequately capture by including degree of urbanization as a dichotomous variable in our analyses.

In single-exposure models, we found that higher exposure to ambient air pollution was associated with higher odds of poor mental wellbeing throughout adolescence. These associations attenuated after adjustment for green space in a buffer of 3000 m and degree of urbanization. We observed higher air pollution concentrations in urban areas than in non-urban areas, and lower levels of green space in buffers of 3000 m in areas with higher concentrations of ambient air pollution ($r_s = -0.76$ to -0.23). This suggests that the associations of air pollution with poor mental wellbeing in this study are partly explained by urban–rural differences in mental wellbeing and lower levels of green space in areas with higher air pollution concentrations. However, associations of OP^{DTT}, $PM_{2.5}$ absorbance and NO_2 were still positive, providing suggestive evidence for a relation between exposure to traffic-related air pollution and poor mental wellbeing in adolescents.

To our knowledge, this is the first study that has examined relationships between exposure to air pollution and self-reported general mental wellbeing in adolescents. One previous study found associations of short-term exposure to ambient air pollution and a higher number of emergency department visits for mental health disorders in individuals aged 8 to 24 years in Toronto, Canada (Szyszkowicz et al., 2020). Another study found that higher residential exposure to $PM_{2.5}$ and NO_2 at age 12 years was associated with an increased odds of major depressive disorders at age 18 years in 284 adolescents in London (Roberts et al., 2019). Finally, a study from Sweden showed that children and adolescents under 18 years of age living in areas with higher exposure to PM_{10} and NO_2 were more likely to have a dispensed medication for a psychiatric disorder (Oudin et al., 2016). The latter two studies (on long-term exposure to ambient air pollution), however, did not take other environmental exposures into account and therefore it is unclear to what extent associations with air pollution were attributable to green space.

In this study, traffic noise was not associated with mental wellbeing throughout adolescence. This is in line with a review showing that data supporting the harmful effects of traffic noise on mental health in children are heterogeneous and limited (Zare Sakhvidi et al., 2018). Consistently, a study from the United States did not observe a higher prevalence of mental health disorders in adolescents with higher exposure to environmental noise (Rudolph et al., 2019). Dzhambov et al. found no direct effect of residential road traffic noise on mental health, but only indirect associations between road traffic noise (through noise annoyance, decreased physical activity and decreased social cohesion) and worse self-reported mental health in the same population of 399 adolescents in Bulgaria (Dzhambov et al., 2017).

4.3. Strengths and limitations

Important strengths of the current study include the repeated measurements of mental wellbeing throughout adolescence and the inclusion of multiple environmental exposures that may be associated with mental wellbeing. Detailed address histories were available for nearly all study participants, which enabled the collection of virtually complete residential exposure data. Moreover, we used multiple indicators to assess residential exposure to green space. Most previous epidemiological studies only used the average NDVI or total percentage of green space in one or several buffers around participants' homes to define exposure to green space (James et al., 2015). We additionally assessed relationships between different types of green space (i.e., urban, natural and agricultural) and mental wellbeing in adolescents.

We acknowledge some potential limitations of our study. We used LUR models that were based on measurement campaigns performed in 2009, we only had traffic noise estimates for 2011, and we only included the average NDVI in buffers of 300 m, 1000 m and 3000 m for 2010. We assumed that the spatial contrasts in green space, air pollution and traffic noise levels remained stable throughout the study period (from 2007 to 2018). We observed high correlations between the average NDVI in buffers of 300 m ($r_s = 0.87$) and 3000 m ($r_s = 0.91$) in 2000/2002 and 2010 for the home addresses of the PIAMA study. This suggests that the spatial contrasts in green space levels in the Netherlands remained constant over a period of 10 years. Furthermore, our assumption is supported by multiple epidemiological studies from Europe that have shown that the spatial variation in air pollution or noise levels remained constant over periods of 7 to 12 years (Fecht et al., 2016; Eeftens et al., 2011; Cesaroni et al., 2012; de Hoogh et al., 2018). Nevertheless, by using purely spatial LUR models in our analyses, we did not account for long-term trends in ambient air pollution concentrations. Ambient concentrations of PM_{10}, $PM_{2.5}$ and NO_2 (measured by routine air quality monitoring stations) have decreased in the Netherlands throughout our study period, i.e., from 2009 to 2018 (European Environment Agency, 2021). For example, the annual average ambient NO_2 concentration in the Netherlands decreased from 29.6 μg/m^3 in 2009 to 23.5 μg/m^3 in 2018 (European Environment Agency, 2021) As a result, we may have overestimated air pollution exposure contrasts for the most recent years, which may have caused some bias in the observed exposure–response relationships.

No data on time-activity patterns were available in this study and exposure estimates were based on residential addresses only. In other words: we did not take into account exposure to green space, ambient air pollution and traffic noise at other locations (e.g., at school). While the residential neighborhood is an anchor in people's lives, people spend a part of their day elsewhere (Helbich et al., 2021). Without mobility data, it is difficult to assess whether our home-based exposure assessment has affected our results.

Another potential limitation of this study is that we have assessed green space in circular buffers of 300 m, 1000 m and 3000 m, instead of using more sophisticated buffers that take into account distances along road networks. It is, however, unknown what buffer sizes and shapes are best suited for representing the different pathways through which green space may impact health (Markevych et al., 2017). Furthermore, we did not have information on the quality of green spaces. Both perceived and objective quality of green spaces (for example, walkability, safety and aesthetics) may be associated with the use of green spaces (Markevych et al., 2017; McCormack et al., 2010). For green space to improve physical activity and social cohesion (i.e., potential pathways through which green space may improve mental wellbeing), actual green space visits are likely important. We only had information on the frequency of green space visits when the PIAMA study participants were 17 years old. We have previously shown that these 17-year-olds did make use of green spaces, mainly for physical and social activities, but that the quantity of residential green space was not related to the frequency of green space visits (Bloemsma et al., 2018). We did not know if and how often our study participants used the green spaces in the specified buffers around their homes when they were 11, 14 and 20 years old.

We have examined potential confounding of associations with one exposure by the other exposures of interest with three-exposure models. In logistic regression, covariates may affect the effect estimate through two separate mechanisms: through confounding (when covariates are associated with both the exposure and the outcome) and through noncollapsibility, which is present when covariates are associated with the outcome (Schuster et al., 2021). In other words: the difference between the univariable- and multivariable effect estimates in our study may not only reflect confounding bias but also a noncollapsibility effect.

Finally, we were only able to include traffic noise levels outside the adolescents' homes. Like most previous studies, we did not have information on potential individual level noise modifiers such as the orientation of the bedroom, indoor insulation and window type. Therefore, there is a possibility of misclassification of individual exposure to traffic noise.

5. Conclusions

Residential exposure to green space may be associated with a better mental wellbeing from age 11 to 20 years in adolescents living in the Netherlands. Higher exposure to ambient air pollution was related to a poorer mental wellbeing in adolescents, but these associations attenuated after adjustment for green space in a buffer of 3000 m, traffic noise and degree of urbanization. Traffic noise was not related to mental wellbeing throughout adolescence. Studies including only one of these three correlated exposures may overestimate associations between the studied exposure and mental wellbeing in adolescents.

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CRediT authorship contribution statement

Lizan D. Bloemsma: Conceptualization, Formal analysis, Writing – original draft. **Alet H. Wijga:** Conceptualization, Supervision, Writing – review & editing. **Jochem O. Klompmaker:** Writing – review & editing. **Gerard Hoek:** Writing – review & editing. **Nicole A.H. Janssen:** Writing – review & editing. **Erik Lebret:** Writing – review & editing. **Bert Brunekreef:** Writing – review & editing. **Ulrike Gehring:** Conceptualization, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2022.107197.

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