**Residential greenspace might modify the effect of road traffic noise exposure on general mental health in students**

**Abstract**

Traffic noise has been linked to mental ill-health but little is known about the impact of residential greenspace on this relationship. In the present study, we investigated whether residential greenspace modified the effect of road traffic noise on general mental health in students. We collected cross-sectional data from 399 participants in the city of Plovdiv, Bulgaria. Road traffic noise (Lden) level was calculated from the strategic noise map of the city. We tested several objective greenspace measures – the Normalized Difference Vegetation Index (NDVI), tree cover density, and Euclidean distance to the nearest green space. Mental health was measured with the General Health Questionnaire (GHQ-12). We conducted moderation analysis and used the Johnson-Neyman (J-N) procedure to identify the values along the continuous moderators (i.e., NDVI 500-m, tree cover 500-m, distance to green space), at which the linear relationship between Lden and GHQ-12 transitioned from statistically significant to non-significant. Results indicated that living in a neighborhood deprived of trees (< 5.84%) enhanced the negative effect of noise, whereas in neighborhoods with higher tree cover density noise had no effect. NDVI and distance to green space showed a similar overall trend, but failed to reach formal statistical significance. Living in a less green neighborhood may enhance the negative effect of road traffic noise on mental health. This observed effect modification may not only be due to disrupted propagation of sound waves, but also to higher recreational quality in greener environment.

**Keywords:** Anxiety; Depression; Green space; Greenness; Moderation; Noise exposure

**1. Introduction**

Traffic noise may relate to mental ill-health through the engendered psycho-physiological stress, which consequently leads to noise annoyance and sleep disturbance (van Kamp and Davies, 2008; van Kamp et al., 2013; Tiesler, et al., 2013). It may also make the residential environment less appealing settings for outdoor recreation (cf. von Lindern et al., 2016), which it turn limits the opportunities to replenish the depleted cognitive and emotional resources needed to handle the psychological wear and tear of everyday adaptive demands (Hartig, 2008; von Lindern et al., 2017). Studies that looked at poor mental health in relation to increased traffic noise levels show mixed results for adults, while data on children is insufficient (van Kamp and Davies, 2008; Stansfeld and Clark, 2015). One possible explanation as to why the effects are not always observed might be that different neighborhood characteristics work as effect modifiers. Since traffic noise and vegetation are interrelated, urban greenspace might fill this role (Dimitrova and Dzhambov, 2017).

Greenspace can shield people from noise and physically disrupt sound propagation (van Renterghem et al., 2015). Further, it may be beneficial for noise perception through psychological mechanisms. For instance, a meta-analysis indicated reduced risk for noise annoyance in people who have a “green view” through their home windows or a good access to greenspace close to the residence (Dzhambov, 2017). Heretofore, both traffic noise (Dzhambov et al., 2018) and noise annoyance (Dzhambov et al., 2018; Zijlema et al., 2017) have been treated as potential mediators linking greenspace to mental health indicators, but the evidence is inconclusive. One reason for the lack of clear findings could be inappropriate model specification, which may have a striking impact on conclusions in environmental health research (cf. Dzhambov et al., 2018). In particular, instead of positioning greenspace as the starting point in the putative causal sequence, it may be conceived as a context, in which the effects of noise are realized (cf. Dimitrova and Dzhambov, 2017). Thus, treating greenspace as a moderator variable, which modifies the effect of noise, rather than treating noise as a mediator between greenspace and mental health, may provide conceptually different and more useful information to those concerned with application (e.g., urban planners and foresters).

To our knowledge, previous research has looked at the associations between greenspace and traffic noise/annoyance (Dzhambov, 2017), between traffic noise/annoyance and mental health (van Kamp and Davies, 2008; van Kamp et al., 2013), and between greenspace and mental health (Gascon et al., 2015), but the above proposed moderation model has not yet been tested explicitly. In the present study, we investigated whether neighborhood greenspace modified the effect of road traffic noise on general mental health in a sample of Bulgarian students. To quantify whether results were affected by how greenspace was defined, we tested a comprehensive set of commonly used objective greenspace measures.

**2. Methods**

***2.1. Study design***

This cross-sectional study is based on a sample collected in October – December 2016 in the city of Plovdiv, Bulgaria. Plovdiv is the second largest city in Bulgaria, with a population of around 342 thousand and a territory of around 102 km2. Students aged 15 – 25 years were recruited from two polytechnic high schools and three universities. After excluding participants who resided in Plovdiv for less than a year and those who did not report their residential address, which was needed for further assignment of geographical variables, we were left with the analytical sample of 399 participants. The sampling process has been described in more detail elsewhere (Dzhambov et al., 2017; 2018).

The study was approved by the school directors, the Regional Inspectorate of Education in Plovdiv, and the Ethics Committee at the institution of the principal investigator. Participants or their parents have signed informed consent forms. No incentives were offered.

***2.2. General mental health***

General mental health during “the past few weeks” was measured with the General Health Questionnaire (GHQ) (Goldberg and Blackwell, 1970). We used the Bulgarian translation of the 12-item form of the questionnaire (GHQ-12) (Mutafova and Maleshkov, 2001; Georgieva, 2010). The GHQ-12 is a valid and reliable measure of common psychiatric disorders in youth, such as depression and anxiety (Tait et al., 2003; Baksheev et al., 2011). It comprises 12 statements with four response options scored from “0” to “3”. We used the GHQ-12 summary score as a continuous variable, with higher values indicating more mental health problems. Cronbach’s α for the whole GHQ-12 was 0.85.

***2.3. Residential road traffic noise***

Road traffic noise exposure data were elicited from the strategic noise map of Plovdiv, prepared according to the European Noise Directive 2002/49/EC. Noise calculations were done with LimA v. 5 according to the French national method “NMPB-Routes-96” and the standard “ХPS 31-133”. The model was calibrated through field measurements according to ISO 1996-1/2005 and ISO 1996-2/1987 (Spectri, 2009). The noise map corresponds to 4 m above the ground level and is available at a resolution of 10 × 10 m. It contains noise levels in the 5-dB contours from 50 dB to 80 dB. Thus, one-unit increase of the day-evening-night noise level (Lden) corresponds to 5 dB. Lden was assigned to the living room façade of each geocoded residential address (Dzhambov et al., 2017; 2018).

***2.4. Greenspace assessment***

Several objective greenspace measures were assessed: The Normalized Difference Vegetation Index (NDVI; Tucker, 1979), tree cover density, and Euclidean distance to the nearest urban greenspace (Dzhambov et al., 2018). They capture different aspects of greenspace with potentially different potential to buffer the effects of noise. Geographic data management and calculations were conducted using the ArcGIS v. 10.1 and v. 10.3 Geographical Information System (GIS) (ESRI, Redlands, CA, USA) and Geospatial Modelling Environment (Spatial Ecology LLC; http://www.spatialecology.com/) softwares.

Euclidean distance (in meters) to the nearest structured urban green space (park, allotment, or recreational ground) was calculated from Open Street Maps (<http://download.geofabrik.de/europe.html>). NDVI (-1 to +1; Tucker, 1979) represents the ratio of reflected light to absorbed light in two vegetation-informative bands of the electromagnetic spectrum – the red band (RED) and the near infrared band (NIR). NDVI is calculated as NDVI = (NIR – RED) / (NIR + RED) and refers to general vegetation level. For these calculations, we used a cloud-free Landsat 8 Operational Land Imager (OLI) satellite image at a resolution of 30 m x 30 m (<https://earthexplorer.usgs.gov/>), obtained on 16th of November 2016. Tree cover density (%) was calculated based on the Tree Cover Density 2012 map developed by the European Environmental Agency at a resolution of 20 m x 20 m (<http://land.copernicus.eu/pan-european/high-resolution-layers/forests/tree-cover-density/view>). NDVI and tree cover density were abstracted as mean values in circular buffers of 100 m, 500 m, and 1000 m. In line with previous studies (Markevych et al., 2014; 2016), we considered the 500-m buffer for the main analysis because it does not only represent the potential of vegetation to physically shield buildings, but also the availability of greenspace in the neighborhood. Other buffers were used as sensitivity analyses. Additionally, we used another satellite image (taken on 11th of July) for creating an alternative NDVI variable capturing maximum spatial contrast in greenness. Finally, we utilized an alternative greenness indicator – the Soil Adjusted Vegetation Index (SAVI; Huete, 1988).

***2.5. Statistical analyses***

To test whether neighborhood greenspace modified the effect of road traffic noise on mental health, first, we used least squares linear regression models. We regressed GHQ-12 on each of the three greenspace measures. Main effects were considered statistically significant at the p < 0.05. The models were adjusted for sex, age, ethnicity, noise sensitivity, socioeconomic status, educational institution, month of data collection, air pollution, presence of water bodies in the respective buffer (or distance to a water body when distance to green space was tested as potential moderator), time spent at home/day, duration of residence, and population density within 1000-m buffer (Dzhambov et al. 2017; 2018).

Next, we conducted moderation analysis using the PROCESS v. 2.16 macro for SPSS (Hayes, 2013). The adjustment set was the same, but we included Lden and each of the greenspace measures in the model along with their interaction term. A heteroscedasticity-consistent standard error estimator was used for all standard errors. The Johnson-Neyman (J-N) procedure, a probing method for examining moderated relationships (Johnson and Neyman, 1936), was used to identify the values along the continuous moderators (NDVI, tree cover density, and distance to green space), at which the linear relationship between traffic noise and mental health transitioned across statistically significant and non-significant. Rather than conditioning on specific values of the moderator (i.e., stratified analysis), the J-N procedure solves the equation for values of the moderator that mark this transition (Montoya, 2016). Because of the small sample size, the criterion for statistical consideration of interactions was relaxed to p < 0.2 (i.e., Type I error rate of 20%) to report relevant effect modification that might otherwise remain undetected (Selvin, 1996; Greenland and Rothman, 1998; Marshall, 2007).

**3. Results**

Majority of the participants were men and Bulgarian. Their mean age was 17.89 ± 2.27 years (Table 1). Correlations between the geographical variables are shown in Supplementary Table S1. Lden was positively correlated with tree cover and population density, and negatively, with NDVI and distance to green space. Of all geographical variables, GHQ-12 was associated only with Lden.

Table 1. Participant characteristics

|  |  |  |
| --- | --- | --- |
| **Characteristics** | | **Total (N= 399)** |
| **Sociodemographics** | |  |
| Men (n, %) | | 271 (67.9) |
| Age (mean, SD) | | 17.89 (2.27) |
| Bulgarian (n, %) | | 366 (91.7) |
| Socioeconomic index (median, IQR) | | -0.04 (1.13) |
|  | |  |
| **Mental health** | |  |
| GHQ-12 (mean, SD) | | 10.80 (6.01) |
|  | |  |
| **Road traffic noise** | |  |
| Lden (n, %) | |  |
|  | 50 – 55 dB(A) | 39 (9.8) |
|  | 55 – 60 dB(A) | 131 (32.8) |
|  | 60 – 65 dB(A) | 112 (28.1) |
|  | 65 – 70 dB(A) | 83 (20.8) |
|  | 70 – 75 dB(A) | 34 (8.5) |
|  |  |  |
| **Greenspace measures** | |  |
| NDVI 500-m (mean, SD) | | 0.29 (0.03) |
| Tree cover 500-m, % (median, IQR) | | 6.46 (5.0) |
| Distance to greenspace, m (median, IQR) | | 196.13 (191.92) |
| SAVI 500-m (mean, SD) | | 0.14 (0.02) |
|  | |  |
| **Other covariates** | |  |
| Noise sensitivity (median, IQR) | | 3.00 (1.0) |
| Duration of residence (n, %) | |  |
|  | 1 – 5 years | 194 (48.6) |
|  | > 5 years | 205 (51.4) |
| Time spent at home/day (n, %) | |  |
|  | ≤ 8 hours | 228 (57.1) |
|  | > 8 hours | 171 (42.9) |
| Population density/km2 (median, IQR) | | 8421.95 (3470.11) |
| Distance to water, m (median, IQR) | | 1006.71 (1096.52) |
| PM2.5 (n, %) | |  |
|  | ≤ 25.0 µg/m3 | 138 (34.6) |
|  | > 25.0 µg/m3 | 261 (65.4) |
| Month of data collection (n, %) | |  |
|  | October | 61 (15.3) |
|  | November | 202 (50.6) |
|  | December | 136 (34.1) |
| Educational institution | |  |
|  | Professional School of Electrotechnology and Electronics | 153 (38.3) |
|  | Professional High School of Mechanical Engineering | 57 (14.3) |
|  | Medical College – Plovdiv | 84 (21.1) |
|  | University of Plovdiv | 67 (16.8) |
|  | Technical University Sofia – Branch Plovdiv | 38 (9.5) |

Abbreviations: GHQ – General Health Questionnaire-12, IQR – interquartile range, Lden – day-evening-night road traffic noise levels at the living room façade, NDVI – Normalized Difference Vegetation Index, PM2.5 – fine particulate matter, SAVI – Soil Adjusted Vegetation Index, SD – standard deviation. All continuous variables are positively coded (i.e., higher values on the variable indicate higher values on the respective factor, except for GHQ, where higher values indicate more mental health problems).

In the linear regression, the main effects of Lden, NDVI 500-m, tree cover density 500-m, and distance to green space (per 50 m) on GHQ-12 were β = 0.49 (95% CI: -0.07, 1.04; p = 0.084), β = -0.27 (95% CI: -20.37, 19.82; p = 0.979), β = 0.02 (95% CI: -0.12, 0.17; p = 0.775), and β = -0.03 (95% CI: -0.11, 0.05; p = 0.425), respectively.

The interaction between Lden and NDVI 500-m was not significant (p = 0.444). Still, the effect of Lden seemed to decrease as NDVI increased. (Figure 1) Conversely, results were clearer for the other greenspace measures. The interaction “Lden × tree cover density 500-m” was significant (p = 0.155) according at our selected α-level. The J-N procedure indicated that in neighborhoods with more than 5.84 % of tree cover, road traffic noise was not anymore detrimental for mental health. (Figure 2) Similar to NDVI, the interaction “Lden × distance to green space” was not formally significant (p = 0.290), but noise negatively affected mental health only in those neighborhoods where green space was within 317 – 644 m from the residence. It also seemed that the greater the distance, the stronger the effect of noise was. (Figure 3)

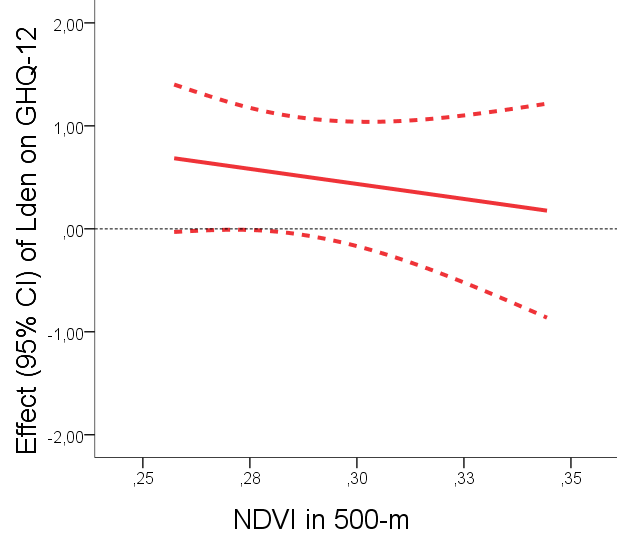


Figure 1. Conditional effect of road traffic noise (Lden) on mental health problems (GHQ-12) depending on overall greenness (NDVI) in 500-m buffer

Note. Values on the y-axis represent the effect of Lden on GHQ-12 at different values of the moderator on the x-axis – the solid line is the unstandardized linear regression coefficient per 5 dB increase of Lden, and the dashed lines are the corresponding limits of the 95% confidence interval. Statistically significant associations (p-value < 0.05) do not cross the reference line (ß = 0). Models are adjusted for sex, age, ethnicity, noise sensitivity, socioeconomic status, educational institution, month, air pollution, water bodies in the respective buffer, time spent at home/day, duration of residence, and population density.

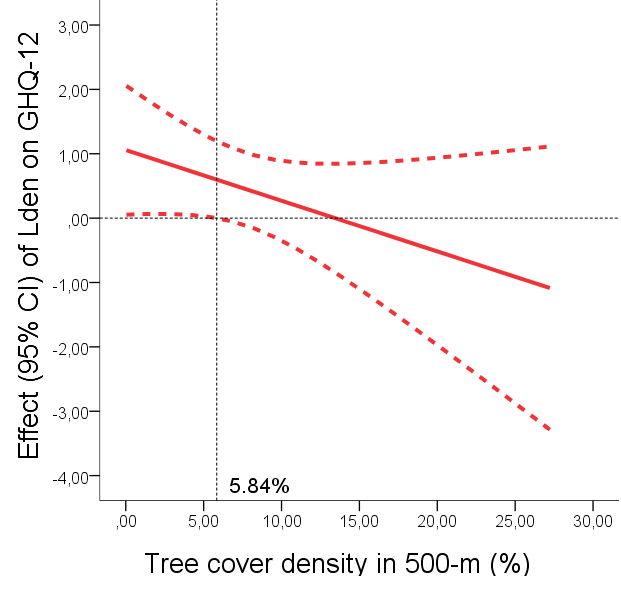


Figure 2. Conditional effect of road traffic noise (Lden) on mental health problems (GHQ-12) depending on tree cover density in 500-m buffer

Note. Values on the y-axis represent the effect of Lden on GHQ-12 at different values of the moderator on the x-axis – the solid line is the unstandardized linear regression coefficient per 5 dB increase of Lden, and the dashed lines are the corresponding limits of the 95% confidence interval. The vertical line represents values at which the effect of Lden on GHQ-12 changes between statistically significant and non-significant. Statistically significant associations (p-value < 0.05) do not cross the reference line (ß = 0). Models are adjusted for sex, age, ethnicity, noise sensitivity, socioeconomic status, educational institution, month, air pollution, water bodies in the respective buffer, time spent at home/day, duration of residence, and population density.

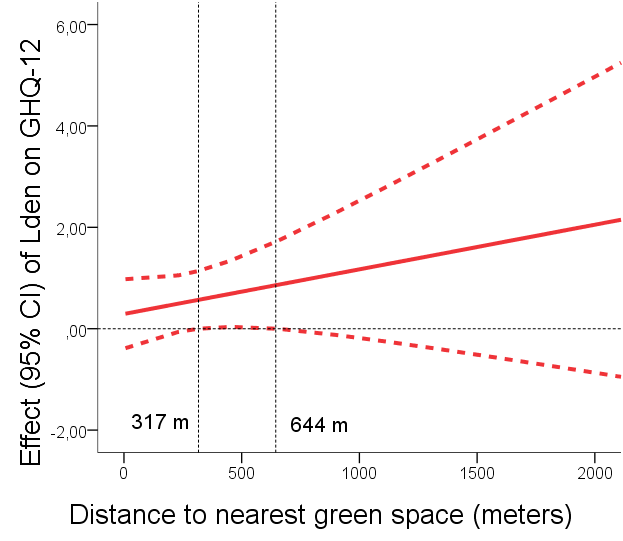


Figure 3. Conditional effect of road traffic noise (Lden) on mental health problems (GHQ-12) depending on the distance to nearest green space

Note. Values on the y-axis represent the effect of Lden on GHQ-12 at different values of the moderator on the x-axis – the solid line is the unstandardized linear regression coefficient per 5 dB increase of Lden, and the dashed lines are the corresponding limits of the 95% confidence interval. The vertical lines represent values at which the effect of Lden on GHQ-12 changes between statistically significant and non-significant. Statistically significant associations (p-value < 0.05) do not cross the reference line (ß = 0). Models are adjusted for sex, age, ethnicity, noise sensitivity, socioeconomic status, educational institution, month, air pollution, distance to water bodies, time spent at home/day, duration of residence, and population density.

In a sensitivity analysis shown in Table 2, tree cover was a significant moderator in the 1000-m buffer, but not in the 100-m buffer. NDVI, on the other hand, did not act as a moderator regardless of the buffer selected. SAVI 500-m was not a moderator either. Of note, when a July satellite image was used to calculate NDVI 500-m, the effect of Lden was significant for NDVI values below the 50th percentile, but the interaction remained non-significant.

Table 2. Conditional effect of road traffic noise (Lden) on mental health problems (GHQ-12) at percentile values of the moderators (greenspace measures)

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Greenspace measures (percentiles)** | | **ß** | **95% CI** | **p** | **Lden ×** **moderator**  **(Interaction p-value)** |
| **Tree cover density 100-m (%)** | |  |  |  | 0.944 |
| 10th | 0.14 | 0.50 | -0.24, 1.23 | 0.186 |  |
| 25th | 1.57 | 0.50 | -0.16, 1.16 | 0.139 |  |
| 50th | 3.62 | 0.51 | -0.08, 1.10 | 0.092 |  |
| 75th | 9.20 | 0.52 | -0.11, 1.16 | 0.105 |  |
| 90th | 15.42 | 0.54 | -0.45, 1.54 | 0.284 |  |
| **Tree cover density 500-m (%)** | |  |  |  | 0.155 |
| 10th | 2.23 | **0.88** | **0.07, 1.70** | **0.034** |  |
| 25th | 3.64 | **0.77** | **0.06, 1.49** | **0.034** |  |
|  | 5.84a | 0.60 | 0.00, 1.20 | 0.050 |  |
| 50th | 6.46 | 0.55 | -0.03, 1.13 | 0.063 |  |
| 75th | 8.52 | 0.39 | -0.19, 0.96 | 0.184 |  |
| 90th | 11.47 | 0.15 | -0.55, 0.86 | 0.664 |  |
| **Tree cover density 1000-m (%)** | |  |  |  | 0.179 |
| 10th | 3.12 | **1.09** | **0.07, 2.12** | **0.037** |  |
| 25th | 4.17 | **0.94** | **0.09, 1.78** | **0.030** |  |
| 50th | 6.40 | **0.60** | **0.02, 1.17** | **0.041** |  |
|  | 6.63a | 0.56 | 0.00, 1.13 | 0.050 |  |
| 75th | 8.11 | 0.34 | -0.27, 0.95 | 0.270 |  |
| 90th | 9.85 | 0.08 | -0.76, 0.91 | 0.857 |  |
| **NDVI 100-m (November)** | |  |  |  | 0.785 |
| 10th | 0.22 | 0.45 | -0.26, 1.15 | 0.218 |  |
| 25th | 0.26 | 0.48 | -0.11, 1.07 | 0.108 |  |
| 50th | 0.29 | 0.52 | -0.06, 1.10 | 0.077 |  |
| 75th | 0.33 | 0.57 | -0.17, 1.32 | 0.132 |  |
| 90th | 0.41 | 0.67 | -0.63, 1.97 | 0.314 |  |
| **NDVI 500-m (November)** | |  |  |  | 0.444 |
| 10th | 0.26 | 0.69 | -0.03, 1.40 | 0.061 |  |
| 25th | 0.28 | 0.58 | -0.01, 1.18 | 0.055 |  |
| 50th | 0.29 | 0.51 | -0.05, 1.08 | 0.076 |  |
| 75th | 0.31 | 0.39 | -0.27, 1.04 | 0.246 |  |
| 90th | 0.34 | 0.18 | -0.86, 1.22 | 0.739 |  |
| **NDVI 1000-m (November)** | |  |  |  | 0.608 |
| 10th | 0.26 | 0.65 | -0.13, 1.44 | 0.104 |  |
| 25th | 0.27 | 0.61 | -0.07, 1.29 | 0.081 |  |
| 50th | 0.29 | 0.51 | -0.05, 1.08 | 0.076 |  |
| 75th | 0.31 | 0.37 | -0.40, 1.14 | 0.349 |  |
| 90th | 0.33 | 0.26 | -0.83, 1.35 | 0.634 |  |
| **NDVI 500-m (July)** | |  |  |  | 0.251 |
| 10th | 0.41 | **0.75** | **0.056, 1.44** | **0.034** |  |
| 25th | 0.42 | **0.68** | **0.046, 1.04** | **0.036** |  |
| 50th | 0.45a | 0.58 | 0.00, 1.15 | 0.050 |  |
| 75th | 0.49 | 0.38 | -0.23, 0.99 | 0.225 |  |
| 90th | 0.53 | 0.17 | -0.65, 0.99 | 0.685 |  |
| **SAVI 500-m (November)** | |  |  |  | 0.828 |
| 10th | 0.12 | 0.55 | -0.21, 1.31 | 0.156 |  |
| 25th | 0.13 | 0.52 | -0.10, 1.14 | 0.099 |  |
| 50th | 0.14 | 0.48 | -0.12, 1.07 | 0.114 |  |
| 75th | 0.15 | 0.45 | -0.23, 1.14 | 0.195 |  |
| 90th | 0.17 | 0.39 | -0.72, 1.50 | 0.493 |  |
| **Distance to greenspace (m)** | |  |  |  | 0.290 |
| 10th | 49.57 | 0.33 | -0.31, 0.98 | 0.306 |  |
| 25th | 103.17 | 0.38 | -0.22, 0.99 | 0.214 |  |
| 50th | 195.70 | 0.46 | -0.10, 1.03 | 0.107 |  |
| 75th | 290.33 | 0.55 | -0.02, 1.11 | 0.057 |  |
|  | 316.78a | 0.57 | 0.00, 1.14 | 0.050 |  |
| 90th | 504.17 | **0.73** | **0.03, 1.44** | **0.040** |  |
|  | 644.43a | 0.86 | 0.00, 1.72 | 0.050 |  |

Abbreviations: ß – unstandardized regression coefficient, CI – confidence interval, m – meters, NDVI – Normalized Difference Vegetation Index, SAVI – Soil Adjusted Vegetation Index. aValues defining Johnson-Neyman significance region. Bold coefficients are statistically significant at p < 0.05. Models are adjusted for sex, age, ethnicity, noise sensitivity, socioeconomic status, educational institution, month, air pollution, water bodies in the respective buffer/distance to water body, time spent at home/day, duration of residence, and population density.

**4. Discussion**

***4.1. General discussion***

This study investigated whether neighborhood greenspace modified the effect of residential road traffic noise on general mental health in students. Moderation analyses showed that living in a neighborhood deprived of trees enhanced the negative effect of noise, whereas in neighborhoods with higher tree cover density noise had no effect. Results for the other greenspace measures (distance to green space and NDVI) showed a similar overall trend but failed to reach formal statistical significance. Evidence of moderation was clearer for tree density possibly because trees (especially their trunks and soil underneath them) have greater potential to reduce sound than vegetation of lower height (cf. van Renterghem et al., 2012; 2015). Another possibility is that because different types of vegetated landscapes reduce noise annoyance to a different degree, trees may be more beneficial (cf. Li et al., 2010). Sound pressure level reduction by vegetation is possible, but oftentimes difficult to achieve and not always efficient in terms of mitigating residents’ negative perceptions (Van Renterghem, 2018). In our correlational analysis, this aspect could not be accounted for. We consider it is likely that greener neighborhoods were simply quieter owing to less traffic noise sources. Such spatial correlation is the reason why vegetation variables such as NDVI are one of the most important predictors of traffic noise in land use regression models (Goudreau et al., 2014; Ragettli et al., 2016).

In addition to a mere physical obstacle for sound propagation, urban greenspace might influence in a positive way people’s perception and evaluative judgment of traffic noise (Van Renterghem, 2018). A recent review by Van Renterghem (2018) summarized the major underpinning psychological mechanisms – visual screening of the noise source, increased restorative quality of the residential environment, and masking of unwanted noise with pleasant nature sounds. Access to a quiet green space may also enable residents to physically escape traffic noise, and thus, encourage their perceived control over the neighborhood sonic environment because they do not feel helpless and trapped in a noisy home (Riedel et al., 2018). Even if they do not actively visit green spaces, residents might perceive the proximity of vegetation as a cure for lower health risk, and in turn experience less cognitive stress and mental health problems (cf. Dimitrova and Dzhambov, 2017; Van Renterghem, 2018). Going further, the combined audio-visual experience of vegetation and nature sounds may fuel the feeling of tranquillity in greenspace (Kang et al., 2016). For instance, nature sounds may improve the perceived acoustic quality of the environment through perceptual or energetic masking of unwanted sounds (Kang et al., 2016). Thus, although traffic noise was proposed as a constraint on neighborhood restorative quality (von Lindern et al., 2016; Dzhambov et al., 2017), some sounds may be beneficial. Positive soundscapes at locations visited for relaxation may have the potential to independently increase people’s perceived restoration (van Kamp et al., 2016). Looking beyond soundscape-related hypotheses, urban greenspace plays a role as a social context not only permitting, but also promoting restoration from different environmental stressors (cf. Markevych et al., 2017). Green spaces provide settings for meeting neighbors, which may strengthen social ties and enhance the sense of community (cf. Kuo et al., 1998), and encourage the pursuit of “green” physical activity (cf. Barton et al., 2016; Hartig, 2008).

***4.2. Strengths and limitations***

To our knowledge, this is the first study to explicitly test whether neighborhood greenspace modifies the effect of road traffic noise on general mental health. We used state of the art objective methods to assess residential noise and three different metrics of greenspace. We also considered a rich set of confounding factors, including noise sensitivity.

Some of the limitations of this study are its cross-sectional design and the fact that it was not population-based, which limits generalizability of our findings. However, use of the objective Lden measure has reduced the likelihood that our estimates are inflated by common method bias and it makes it harder to claim reverse causality with respect to the causal link traffic noise – mental health. Neighborhood self-selection, that is, relocation of people with better mental health to a less-polluted neighborhood, is not a likely scenario in Bulgaria because many Bulgarians may not be able to afford such a “luxury”.

The sample was originally collected to study the underlying processes linking greenspace to mental health (Dzhambov et al., 2018). The youth age group was specifically targeted because most disorders begin during that period (Patel et al., 2007). The student occupation was also of interest because being a student is commonly perceived as a highly stressful occupation, and chronic stress is likely to increase the risk of underlying disorders. The GHQ screens for this risk with items that tap chronic stress. However, our sample was very selective, so it was not representative of all youth in Plovdiv – some young residents may already be employed and not studying; larger proportion of the sample were males due to the fact that some of the included educational institutions were polytechnic schools. Notwithstanding, the internal validity of our study should still be high because we controlled for a wide range of sociodemographic and residential confounding factors.

This study probably lacked power to detect significant effect modification (i.e., interaction terms) by NDVI and distance to green space. Although the J-N procedure identified values of distance to green space that marked the transitioning between significant and non-significant effect of Lden, we could not statistically prove moderation. In addition, we probably lacked statistical power to detect a significant effect of Lden when distance to green space was above 644 m because few participants (7.27%) resided so far from a structured green space. Looking at Figure 3, this explanation seems plausible.

The noise map we could obtain for the study area was classified into 5-dB contours, and therefore noise levels at addresses in the same noise band could not be discerned. This ultimately led to some exposure misclassification, and consequently, underestimation of the exposure-response relationship between noise and mental health.

All greenspace measures we used were two-dimensional, meaning that it was not possible to ascertain that greenspace physically reduced noise exposure. Moreover, few noise models adequately account for acoustic shielding by green barriers (Garg and Maji, 2014). Therefore, we reckon that the association between noise and greenness observed in our study is spatial, rather than causal. NDVI probably represents the level of urbanization in our sample because noise levels are lower in the periphery of Plovdiv, where the general greenness of the neighborhoods is higher. To address this issue, we adjusted our models for population density as a proxy for urbanicity. It was also reassuring that we observed significant moderation for tree cover, which, unlike NDVI, was higher in the core of Plovdiv. We also lacked data regarding what floor participants lived on, which may lead to exposure misclassification (cf. Tiesler, et al., 2013). Future studies should use deep learning algorithms and measured noise at the façade level to take into account the three-dimensional parameters of urban vegetation and its position relative to the propagation path between the noise source and the receiver, i.e., the actual disruption of sound propagation by vegetation (cf. Markevych et al., 2017; Dzhambov, 2017).

According to multiple previous studies (cf. Dzhambov, 2017), visible greenness from home is associated with lower noise annoyance. Unlike Van Renterghem and Botteldooren (2016), however, we did not assess objectively participants’ view on vegetation from home. We had data on perceived green view through the living room window, but that variable was self-reported, and hence, could be reversely affected by individual’s mental health status.

***4.3. Implications***

Different interventions intended to reduce the adverse health outcomes due to traffic noise were recently summarized and classified in a World Health Organization systematic review by Brown and van Kamp (2017). Most technical interventions involve mitigating residents’ exposure by disrupting the propagation path between the noise source and the receiver, the so called source and path interventions. Still, availability of greenspace was specifically mentioned in the rubric “Other physical interventions” (Brown and van Kamp, 2017), recognizing that, in addition to changing exposure, neighborhood green spaces may be perceived as a place to get a break from traffic noise, and thereby ameliorate the negative reaction to noise (Gidlöf-Gunnarsson and Öhrström, 2007; Dzhambov and Dimitrova, 2015).

Establishing dose-response curves for traffic noise is not a new concept and their application to greenspace and health research was also recently heralded to facilitate the application of scientific evidence in urban planning (Markevych et al., 2017). Urban greening is viewed by experts as an important factor for public health protection (van den Bosch and Nieuwenhuijsen, 2017), however, few guidelines exist on how much green is just enough, and the evidence base for explicit recommendations is still limited (Markevych et al., 2017; WHO, 2016). Furthermore, to our knowledge, no study has previously investigated how objective, quantitative measures of greenspace relate to the potential of greenspace to moderate the relationship between traffic noise and mental health. One questionnaire study, though, indicated that perceived access to green areas might moderate the association between noise and self-rated health (Dimitrova and Dzhambov, 2017). Self-reports are valuable for understanding the person-environment interaction but objective measures are needed to design “targeted, evidence-based greenspace interventions for the health promotion of urban residents” (WHO, 2016). A meta-analysis yielded pooled OR for noise annoyance of 0.58 (95% CI: 0.39, 0.86) in people living within 200 – 400 m of a green space (Dzhambov, 2017). That might strengthen the case for recommending a distance from home to a green space of around 300 – 500 m (Annerstedt van den Bosch et al., 2016; European Commission, 2001). Although it was proposed to use smaller buffers (e.g., 50 – 100 m) with remotely-sensed vegetation measures to capture streetscape greenness when studying its effect on noise perception (Dzhambov, 2017; Markevych et al., 2017), our moderation tests were significant only for tree cover density within 500-m and 1000-m buffers. Therefore, both street trees and trees in structured green spaces should be considered, as the benefits of greenspace for noise perception may extend beyond blocking sound waves and stress reduction by direct visual exposure to vegetation.

It should be noted that, depending on the scale of analysis and urban morphology (e.g., greenspace pattern), the spatial association between greenspace and traffic noise may vary – in some settings “green” may not necessarily mean “quiet” (Margaritis and Kang, 2016; 2017). Thus, our findings may be specific to the urban fabric of Plovdiv and should be tested in other settings before explicit recommendations can be made to urban planners seeking to reduce the mental health effects of traffic noise through evidence-based greenspace interventions.

**5. Conclusion**

Living in a neighborhood deprived of trees may enhance the negative effect of road traffic noise on mental health. This observed modification may be attributed to the various functions served by urban greenspace not only as a physical barrier for sound waves, but also as an important feature of different recreational settings in the urban environment. Similar, although statistically non-significant trend, was observed for overall greenness and distance to green space.

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**Conflicts of interests**

We declare no actual or potential conflicts of interests.

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