**Pathways linking residential noise and air pollution to mental ill-health in young adults**

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**Running title**: Residential noise/air pollution and mental ill-health

**Abstract**

**Background**: Recent years have seen growing, but still tentative, evidence of the potential associations of environmental noise and air pollution with mental disorders. In the present study, we aimed to examine the associations between residential noise and air pollution exposures and general mental health in young adults with a focus on underlying processes. **Methods**: We sampled 720 students (18 – 35 years) from one university in the city of Plovdiv, Bulgaria. Residential noise (LAeq; day equivalent noise level) and air pollution (NO2) were assessed at participant’s residential address by land use regression models. General mental health was measured with a short form of the General Health Questionnaire (GHQ). The following putative mediators were considered: annoyance from environmental pollution, sleep disturbance, restorative quality of the neighborhood, neighborhood social cohesion, and commuting/leisure time physical activity. Structural equation modelling was used to analyze the theoretically-indicated interplay between exposures, mediators, and GHQ. **Results**: We observed an association between higher LAeq and GHQ, in which environmental annoyance and neighborhood restorative quality emerged as key mediators. First, LAeq was associated with higher annoyance, and through it with lower restorative quality, and then in turn with lower physical activity, and thus with higher GHQ. Simultaneously, higher annoyance was associated with higher sleep disturbance, and thereby with higher GHQ. NO2 had no overall association with GHQ, but it was indirectly associated with it through higher annoyance, lower restorative quality, and lower physical activity working in serial. **Conclusion**: We found evidence that increased residential noise was related to mental ill-health through several indirect pathways. Air pollution was associated with mental health only indirectly.

**Keywords:** Annoyance; Anxiety; Depression; Physical activity; Restoration; Social cohesion; Traffic noise

**1. Introduction**

 The global burden of mental disorders is continuously rising and inflicts considerable social and economic losses to society. Some 4% of the population suffers from a common mental disorder – that is, 322 million people in the world live with depression, and 264 million, with anxiety (WHO, 2017). That translates into 50 million years lived with disability due to depression and 24.6 million due to anxiety (WHO, 2017).

In addition to genetic and psycho-social risk factors (WHO, 2016), recent years have seen growing, but still tentative and inconclusive, evidence of the potential detriment of environmental noise and air pollution (Stansfeld et al., 1996; Orban et al., 2016; Lim et al., 2012; Power et al., 2015; Tzivian et al., 2015). Several mechanistic hypotheses have been proposed to explain observed associations. For instance, individuals exposed to noise report annoyance (Guski et al., 1999), which has been proposed as a mediator linking noise to mental ill-health (van Kamp et al., 2013). Our previous study (Dzhambov et al., 2017) illustrated how road traffic noise may be associated with higher noise annoyance, which in turn may increase interpersonal distance and social isolation in the neighborhood, and thus lead to mental ill-health. Increased annoyance may also constrain psychologically-restorative person-environment encounters in the neighborhood, and consequently limit outdoor physical activity and social interactions, and in turn lead to mental ill-health.

According to Frei et al. (2014), noise annoyance mediates the effect of nighttime noise on self-reported sleep quality, whereas objective sleep quality is independent of annoyance. Our previous model, however, did not consider sleep disturbance, which may be an important mediator between noise and mental health (Tiesler et al., 2013; Sygna et al., 2014) or lead to daytime sleepiness and decreased willingness to engage in physical activity (Roswall et al., 2017), which in turn may diminish mental health (Dzhambov et al., 2017). Another caveat that should have been considered is that there may be a reciprocal association between poor mental health and noise annoyance (van Kamp et al., 2013; Schreckenberg et al., 2017). Incorrect model specification and failure to account for the fact that mediators may be intertwined could be one of the reasons for the heterogeneous findings in the literature (Dzhambov et al., 2017).

 Previous studies have focused on the biological pathways linking air pollution to mental health (Tzivian et al., 2015). Some air contaminants may influence neurobehavioral functions by entering the brain directly through the olfactory system (Doty, 2008) or by promoting pro-inflammatory cytokines that penetrate the blood-brain barrier (Genc et al., 2012). Thus, fine particles may induce neuroinflammation and neurodegeneration (Calderón-Garcidueñas et al., 2015). In addition to these biological pathways, perceived air pollution engenders cognitive stress, which leads to perceived symptoms of ill-health (Elliott et al., 1999; Stenlund et al., 2009; Claeson et al., 2013; Klaeboe et al., 2008). Furthermore, akin to noise, air pollution may reduce neighborhood restorative quality through higher annoyance (von Lindern et al., 2016), and thereby inhibit mental health-supporting behaviors outdoors (cf. Dzhambov et al., 2018). However, epidemiological research is still in its infancy and the concurrent effects of noise and air pollution have received modest attention in the literature (Tzivian et al., 2015).

 The present study examines associations between residential noise and air pollution exposures and general mental health in a sample of students. We specifically focus on different underlying processes. (Figure 1) Understanding how these pathways may work together should enable practitioners to adequately tailor future preventive interventions for the improvement of mental health.



Figure 1. Conceptual diagram showing theoretically-indicated pathways linking residential noise and air pollution to mental ill-health

**2. Methods**

*2.1. Study design and sampling*

Data were collected between October and November 2017 from the Medical University in the city of Plovdiv, which is the second largest city of Bulgaria. To be included in our study, students had to be aged 18 – 35 years and to reside in Plovdiv or the near provinces in Southern Bulgaria for at least six months. (See Supplementary Figure S1 for location of the study area) We targeted potential participants with different ethnic and cultural background, age, and program enrollment (Faculties of Medicine, Dental Medicine, Pharmacy, Public Health, and the Medical College) to ensure sufficient variation in the data. During a class/lecture, members of the research group advertised the study as an omnibus survey on “neighborhood environment and quality of life”, and asked the students to complete a questionnaire. Since a member of the research group was present, participants had the opportunity to give feedback and receive clarifications about each question. In addition to questions on sociodemographic factors, residential environment, mental and general health, participants were asked to report their residential address for subsequent assignment of air pollution, noise, and other geographic variables. The study design was approved by the Ethics Committee at the Medical University of Plovdiv (Dzhambov et al., 2018). Participants signed informed consent forms. No incentives were offered.

Of the 1 000 students invited, 823 agreed to participate (82% response rate). Residential addresses were converted to geocodes manually by inspecting each address with the help of Google maps. We were able to successfully geocode the residences of 720 students (89.2% residing in Plovdiv), which comprised our analytical sample. The rest had provided vague description of their address or no address at all.

*2.2. Exposures to residential noise and air pollution*

Residential noise exposure (LAeq; day equivalent noise level) was obtained by applying a land use regression (LUR) model. The LUR was developed specifically for this study and is based on noise measurements carried out by the Regional Health Inspection at 40 locations (traffic sites, industrial sites, sites in residential and recreational areas) in Plovdiv in 2016 (range: 62.4 – 73.5 dB(A)). Measurements were conducted over the 12-hour period from 07.00 to 19.00 hours, according to the ISO 1996-2:1987 (SPECTRI, 2017). Predictor variables were derived from the Geographical Information System. Regression equation followed a supervised forward stepwise selection procedure previously described by Aguilera et al. (2015). The final LUR has an adjusted R2 of 0.72 and leave-one-out cross validation R2 of 0.65. Further details are reported elsewhere (Dzhambov et al., in press).

Nitrogen dioxide (NO2) was calculated as a proxy for residential traffic-related air pollution. We used a global LUR model for NO2 with an adjusted R2 of 0.52 and a root-mean-square error of 4.8 ppb (9.02 μg/m3) (observed range 0 – 47 ppb (0 – 88.36 μg/m3) in the European region) (Larkin et al., 2017). Briefly, the model was constructed by using data from air quality monitoring stations, satellite-based NO2 and other commonly used geographic variables related to air pollution (Larkin et al., 2017). Predicted LAeq and NO2 values (n ≈ 1%) outside the observed range of the measurements used to construct the respective LURs, were recoded to the closest observed value. Geographic data management and calculations were carried out using ArcGIS 10.3-10.4 (ESRI, Redlands, CA, USA).

*2.3. General mental health*

 Mental health in the past month was measured with a modified 11-item form of the General Health Questionnaire (GHQ) translated in Bulgarian (Georgieva, 2010; Mutafova and Maleshkov, 2001). The GHQ screens symptoms of common psychiatric disorders (i.e., depression, anxiety) (Goldberg and Blackwell, 1970) and has been successfully used in previous studies on traffic noise and mental health (e.g., Stansfeld et al., 1996; von Lindern et al., 2016; Dzhambov et al., 2017). Since we did not want to artificially inflate the correlation between GHQ and the sleep disturbance variable in our dataset, one of the items asking about “losing sleep over worry” was excluded from the analyses. Each of the remaining 11 items was scored from 0 to 3, with a higher summary score indicating worse mental health (Cronbach’s alpha = 0.87). The GHQ was included in the analyses as a continuous variable to increase the statistical power.

*2.4. Potential mediators*

 Candidate mediators were selected based on a previously delineated hypothesis that residential noise and air pollution might harm mental health not only directly acting as stressors, but also indirectly by limiting the opportunities to recover from the wear-and-tear of other daily stressors (von Lindern et al., 2016; Dzhambov et al., 2017). Hence, the following putative mediators were considered: annoyance from environmental pollution, sleep disturbance, perceived neighborhood restorative quality, neighborhood social cohesion, and commuting/leisure time physical activity. In the questionnaire, “neighborhood” was described as the area within a 10-15-minutes walking distance around the residential address. All self-report measures referred to the last month.

Following von Lindern et al. (2016), we combined individual annoyances in the dwelling and the neighborhood from noise, air pollution, and vibration. However, our approach differed in that we considered annoyance due not just to traffic, but to other sources as well. This choice was made because we calculated NO2 from all sources; the measurements used to construct the LUR for noise were conducted not just at traffic sites, but also in residential and recreational areas; and the factors to which we hypothesized annoyance should be related were probably affected by multiple sound sources (e.g., neighbors preventing an individual from falling asleep, even though he might live on a street with little traffic). The four items we used mimic the phrasing and response options of the 5-point verbal International Commission on Biological Effects of Noise annoyance scale (Fields et al., 2001). The questions were formulated as following: “*How much does road traffic noise bother, disturb, or annoy you?*”. Similar questions asked about annoyance due to: (a) noise from neighbors/construction/recreational establishments, (b) air pollution, and (c) vibration from different sources (e.g., street traffic, construction, neighbors, loud music). Possible responses were: “0 = Not at all”, “1 = Slightly”, “2 = Moderately”, “3 = Very”, and to “4 = Extremely”. The items were correlated in the range 0.41 – 0.63. The mean of responses served as a measure of annoyance in the living environment. In order to give noise annoyance equal weight to air pollution and vibration annoyances, we calculated the mean of the four items by the formula: ((traffic noise annoyance + residential noise annoyance)/2 + air pollution annoyance + vibration annoyance)/3. Cronbach’s alpha for the whole scale is 0.81.

Self-reported sleep disturbance was measured by averaging responses to two items (r = 0.47), mimicking previously used questions (cf. Basner and McGuire, 2018): “*How often do you have trouble falling asleep at night?*” and “*How often do you wake up in the middle of the night?*”. Possible responses were measured on an 11-point scale ranging from “0 = Never” to “10 = Every night”.

Perceived restorative quality of the neighborhood was assessed with items from the Perceived Restorativeness Scale (PRS) (Hartig et al., 1997a; 1997b), originally intended to enable researchers to study the contributions of the components of restorative experience described in the Attention Restoration Theory (Kaplan, 1995; Kaplan and Kaplan, 1989). Consistent with previous studies with the PRS (Dahlkvist et al., 2016; von Lindern et al., 2016; Dzhambov et al., 2018), only the “Being away” and “Fascination” subscales were used. These subscales tap experiences of psychological distance and positive engagement with the environment. Following Lindal and Hartig (2013; 2015), we used single items to reduce questionnaire length and response burden: “*My neighborhood has places where the time spent gives me a break from my day-to-day routine and where I can get away from the things that usually demand my attention.*” and “*My neighborhood has places that are fascinating and where my attention is drawn to many interesting things.*”, respectively. Agreement with each statement is measured on an 11-point scale. After examining the correlation between the two items (r = 0.71), we decided to use their mean to avoid collinearity (cf. Dzhambov et al., 2018; von Lindern et al., 2016).

To measure perceived neighborhood social cohesion, we used three items from the brief form of the Perceived Neighborhood Social Cohesion questionnaire (PNSC-BF) (Dupuis et al., 2017; 2016), which was previously translated to Bulgarian (Dzhambov et al., 2018). Originally, the PNSC-BF comprised nine items measuring three dimensions: “Trust in people”, “Attachment to neighborhood”, and “Tolerance and respect”. To reduce questionnaire length, the items pertinent to each of these subscales were combined into a single statement: “*Most people in my neighborhood can be trusted; they wouldn’t take advantage of me; and, if I were in trouble, they would come to my aid*.”, “*Most people in my neighborhood are friendly; they are concerned with the interests of others, and help each other.*”, and “*People in my neighborhood respect each other and accept others who are not like them.*”, respectively. Responses are made on a 7-point scale. The three items are highly correlated (r = 0.66 – 0.79) and Cronbach’s alpha for our three-item scale is 0.88.

 Participants’ physical activity energy expenditure was measured with a self-report tool, the Short Questionnaire to Assess Health-enhancing physical activity (SQUASH) (Wendel-Vos et al., 2003; Campbell et al., 2016). The questions asked about different types of physical activity performed during an average week in the past month and about the number of days/week, time/day, and effort they took. We assigned metabolic equivalent of task (MET) values to each activity according to its intensity (3 METs for “light”, 5.2 METs for “moderate”, and METs 6.5 for “intense”), and computed total daily physical activity energy expenditure (Campbell et al., 2016). For MET values associated with different sports, we used the “Compendium of Energy Expenditures for Youth” (Ridley et al., 2008) by using data on participants’ self-reported body weight. Since physical activity was right-skewed, it was cube root-transformed to achieve closer-to-normal distribution before including it in the models.

*2.5. Confounders*

We gathered data on participants’ age, sex, ethnicity (Bulgarian *vs* other), duration of residence (< 5 years *vs* ≥ 5 years), average time spent at home/day (< 8 hours *vs* ≥ 8 hours), and month of data collection (October *vs* November). Additionally, we used a single item to assess perceived individual-level economic status (“*Having in mind your monthly income, how easy is it for you to “make ends meet”, meet your expenses without depriving yourself?*”; “0 = Very difficult” to “5 = Very easy”). Population (total number of people) in a 500-m buffer around the address was used as a proxy for urbanicity. It was calculated from the 2011 Census population grid (1 km x 1 km) developed by the National Statistical Institute of Bulgaria (<http://www.nsi.bg/en/content/12309/population-grid-1-sqkm-census-2011>).

*2.6. Statistical analysis*

Most self-reported variables had less than 5% missing values. LAeq had 11.3% missing, as the LUR was only applied to address points in Plovdiv where noise measurements were conducted. Due to the reasonably low proportion of missing data, they were replaced using the expectation maximization algorithm (Dempster et al., 1977; Pigott, 2001). To improve the prediction of missing values, we included in the imputation procedure all the variables included in the multivariate analysis models, as well as several auxiliary variables (neighborhood green- and bluespace, perceived noise and air pollution in the neighborhood, perceived neighborhood economic status, residential satisfaction, stress, university faculty, smoking, alcohol consumption, and self-rated health).

Before testing specific underlying mechanisms, we examined the overall relationship between LAeq/NO2 and GHQ using ordinary least squares (OLS) regression. All control variables were included in the models based on *a priori* knowledge. Crude model was adjusted for age and sex; Main model was additionally adjusted for ethnicity, individual-level economic status, duration of residence, time spent at home/day, population, and month of data collection; and Full model was further adjusted for potential mediators (environmental annoyance, sleep disturbance, restorative quality, social cohesion, and physical activity). We also considered a sensitivity analysis, in which LAeq and NO2 were not adjusted for each other. In stratified sensitivity analysis, we tested the overall association between LAeq/NO2 and GHQ for modification by sex, ethnicity, duration of residence, and time spent at home/day. Effect modification was claimed in case of a significant interaction term (LAeq/NO2 x putative moderator) (Wald’s p-value < 0.05).

The main analysis was based on structural equation modeling (SEM) to account for the theoretically-indicated interplay between factors specified in Figure 1. Small's test of multivariate normality showed the assumption of multivariate normality to be violated, therefore we used a maximum likelihood minimization function with bootstrap-generated confidence intervals and standard errors for all regression paths (10 000 samples) (Kelley, 2005; Haukoos and Lewis, 2005; Brown, 2006). Control variables included in SEM were the same as in the OLS regression; however, only marginally significant confounding paths (p < 0.1) were retained in SEM. Error terms of LAeq and NO2 were *a priori* allowed to covary. Goodness of fit was evaluated by using multiple indices to ensure a more conservative and reliable evaluation of the solution – the χ²-test, standardized root mean square residual (SRMSR), root mean square error of approximation (RMSEA), and comparative fit index (CFI) – according to suggestions for acceptable model fit provided in Hu and Bentler (1999): non-significant χ2 (p > 0.05), RMSEA (≤ 0.06; 90% CI ≤ 0.06), SRMSR (≤ 0.08), and CFI (≥ 0.95). Over 95% of the normalized residuals ≤ |2.58| were expected from a good-fitting model (Brown, 2006). Modification indices and standardized residuals were inspected to improve model fit when suggested model re-specification was justified by scientific logic.

The initial model (Model 0) had poor fit to the data: χ2 (436) = 1421.430, p < 0.001, SRMSR = 0.065, RMSEA = 0.056 (90% CI: 0.053, 0.059), CFI = 0.855. Inspection of the standardized residuals and modification indices indicated some localized points of ill fit in the solution. Hence, we re-specified it by drawing links, which reflected plausible covariances between participants’ characteristics (without implying causation), and a regression path from ethnicity to LAeq. We also decided to remove the non-significant direct path from LAeq to sleep disturbance, which is consistent with suggestions that annoyance may be a better predictor of perceived noise-induced sleep disturbance than noise exposure (van den Berg et al., 2014; Frei et al., 2014). We also assumed that this path could be non-significant due to methodological issues (i.e., LAeq was calculated to represent noise level at postcode-level, rather than at the bedroom façade of the dwelling). (See Supplementary Figure S2 for comparison of Model 0 and Model 1)

Next, we fitted a non-recursive Model 2 nested within Model 1, in which we specified a bidirectional association between GHQ and environmental annoyance and a covariance between their error terms (cf. Schreckenberg et al., 2017). This analytic technique followed considerations of Wong and Law (1999) and allowed to approximate cross-lagged reciprocal effects using our cross-sectional data. The model with lower deviance statistics (χ2, Akaike Information Criterion (AIC) and Bayesian Information Criterion (BCC)) was considered the better fitting model (Kenny and Kashy, 2006).

Results were considered statistically significant at the p < 0.05 level, and mediation was considered when the indirect path (effect) significantly exceeded zero, regardless of the significance of the total effect (Zhao et al., 2010). Marginally significant (p < 0.1) indirect effects are further discussed only as suggestive evidence of mediation.

**3. Results**

*3.1. Sample characteristics*

 Participants’ characteristics are shown in Table 1. Majority of them were women and Bulgarian. Mean age was 21 years. Univariate correlations between the variables indicated that higher GHQ was associated with higher LAeq, environmental annoyance, and sleep disturbance, and with younger age, lower income, and lower physical activity. LAeq and NO2,on their part, were associated with higher population density, and LAeq – with higher annoyance, and sleep disturbance. LAeq was similarly correlated with traffic annoyance, noise annoyance from other sources, and vibration annoyance. (For more details, see Dzhambov et al. (in press).)

Table 1. Participant characteristics (N= 720)

|  |  |  |
| --- | --- | --- |
| **Characteristic** |  | **Min – max**  |
| **Sociodemographic factors**  |  |  |
| Sex: Male (n, %) | 243 (33.8) | . |
| Age (median, IQR) | 21.00 (3.00) | 18 – 35  |
| Ethnicity: Bulgarian (n, %) | 533 (74.0) | . |
| Economic status (mean, SD) | 2.64 (1.20) | 0 – 5  |
|  |  |  |
| **Mental health**  |  |  |
| GHQ (mean, SD) | 10.01 (5.43) | 0 – 33  |
|  |  |  |
| **Candidate mediators** |  |  |
| Environmental annoyance (mean, SD) | 1.61 (0.89) | 0 – 4  |
| Sleep disturbance (median, IQR) | 2.00 (3.00) | 0 – 10  |
| Restorative quality (median, IQR) | 3.50 (3.00) | 0 – 10  |
| Social cohesion (mean, SD) | 2.89 (1.39) | 0 – 6  |
| Physical activity, EEa (median, IQR) | 221.27 (363.46) | 0 – 3 087.37 |
| LAeq,dB(A) (mean, SD) | 67.05 (1.73) | 62.4 – 72.63  |
| NO2,µg/m3 (mean, SD) | 15.18 (3.03) | 0 – 27.17 |
|  |  |  |
| **Other covariates**  |  |  |
| Settlement: Plovdiv (n, %) | 642 (89.2) | . |
| Duration of residence: ≥ 5 years (n, %) | 276 (38.3) | . |
| Time spent at home/day: ≥ 8 hours (n, %) | 394 (54.7) | . |
| Population 500-m (median, IQR) | 9107.70 (3941.80) | 37.65 – 21 429.88 |
| Month: October (n, %) | 328 (45.6) | . |

Abbreviations: EE – energy expenditure, GHQ – General Health Questionnaire, IQR – interquartile range, LAeq – day equivalent noise level, NO2 – nitrogen dioxide, 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 worse mental health). aBefore cube root-transformation. Descriptives for non-normally distributed continuous variables are presented as median and IQR.

*3.2. Overall association between LAeq and NO2 and GHQ*

 Results of the linear regressions are shown in Table 2. LAeq was associated with higher GHQ only in the Crude model. Following further adjustments, the association was attenuated and no longer significant. For NO2, we did not observe an association with GHQ in any of the models. Even if NO2 was not adjusted for LAeq, it was not associated with GHQ (data not shown).

 Stratified analysis indicated that both LAeq and NO2 were stronger associated with GHQ in non-Bulgarians. (Supplementary Figure S3) In addition, LAeq was stronger associated with GHQ in those living at their current address for less than 5 years, and NO2 – in men.

 Table 2. Association between residential noise (per 5 dBA)and air pollution (per 10 µg/m3) and mental ill-health (GHQ)

|  |  |  |
| --- | --- | --- |
| **Model** | **β (95% CI)** | **p-value** |
| **Crude**  |  |  |
|  | LAeq  | **1.954 (0.757, 3.151)a** | **0.001** |
|  | NO2  | -0.391 (-1.764, 0.982) | 0.576 |
|  |  |  |
| **Main** |  |  |
|  | LAeq  | 0.660 (-0.434, 1.755) | 0.237 |
|  | NO2  | -0.665 (-1.935, 0.605) | 0.304 |
|  |  |  |  |
| **Full** |  |  |
|  | LAeq  | 0.536 (-0.446, 1.517) | 0.284 |
|  | NO2  | -0.753 (-1.889, 0.383) | 0.194 |

Abbreviations: GHQ – General Health Questionnaire, LAeq – day equivalent noise level, NO2 – nitrogen dioxide. Regression coefficients are unstandardized. Higher GHQ score is indicative of poorer mental health. Adjustments: LAeq and NO2 are mutually adjusted; Crude model is adjusted for age and sex; Main model is additionally adjusted for ethnicity, individual-level economic status, duration of residence, time spent at home/day, population, and month of data collection; Full model is additionally adjusted for potential mediators: environmental annoyance, sleep disturbance, restorative quality, social cohesion, and physical activity. aCoefficient is statistically significant at p < 0.05.

*3.3. SEM linking LAeq and NO2 to GHQ*

 We obtained a reasonably well-fitting final model (Model 1): χ2 (424) = 825.575, p < 0.001; CFI = 0.941; RMSEA = 0.036 (90% CI: 0.033, 0.040); SRMR = 0.044; AIC = 1033.575; BCC = 1043.581. (Figure 2) Supplementary Table S1 shows the correlation matrix of the variables in the model.



Figure 2. Structural equation model showing the estimated paths linking LAeq and NO2 to mediators and mental ill-health

Abbreviations: GHQ – General Health Questionnaire, LAeq – day equivalent noise level, NO2 – nitrogen dioxide. Standardized regression weights with their significance level (in parenthesis) are given for each path. R2 – squared multiple correlation. Bold coefficients are statistically significant at p < 0.05. Higher GHQ score is indicative of poorer mental health. Control variables, covariances, and errors terms are not displayed to enhance readability.

Overall, 56% of the variance in GHQ was explained. Table 3 shows estimated total, direct, and indirect effects. The standardized total effect of LAeq was significant and fully mediated by several serial mediation components. More specifically, LAeq was associated with higher annoyance, and through it with lower neighborhood restorative quality, and in turn with lower physical activity, and in turn with poorer mental health (path 3). Simultaneously, higher annoyance was associated with higher sleep disturbance, and in turn with poorer mental health (path 6). NO2 had no total effect on GHQ. However, it was indirectly associated with GHQ through annoyance, restorative quality, and physical activity working in serial (path 10). Another serial mediation path through annoyance and sleep disturbance was marginally significant (p < 0.1) (path 13). When we repeated the SEM analysis using only the traffic noise annoyance item instead of the average of the two noise annoyance items, we obtained the same results, except that the indirect effect of NO2 through annoyance and sleep disturbance transitioned from marginally significant to significant (β = 0.004; 95% CI: 0.001-0.01; p = 0.023).

Table 3. Total, direct, and indirect effects of LAeq and NO2 on mental ill-health (GHQ) in the structural equation model

|  | **β (95% CI)** | **p-value** |
| --- | --- | --- |
| **LAeq**  |  |  |
| Standardized total effect  | **0.069 (0.006, 0.131)a** | **0.034** |
| Standardized direct effect  | 0.034 (-0.026, 0.095) | 0.265 |
| Standardized total indirect effect  | **0.035 (0.010, 0.065)a** | **0.004** |
| Unstandardized specific indirect effects through: |  |  |
| (1) LAeq → Annoyance | 0.003 (-0.001, 0.011) | 0.110 |
| (2) LAeq → Annoyance → RQ → SC | 0.00005 (-0.00006, 0.0003) | 0.301 |
| **(3) LAeq → Annoyance → RQ → PA** | **0.00009 (0.00001, 0.003)a** | **0.010** |
| (4) LAeq → Annoyance → RQ  | 0.0002 (-0.0002, 0.001) | 0.260 |
| (5) LAeq → Annoyance → SC  | 0.0002 (-0.0003, 0.001) | 0.365 |
| **(6) LAeq → Annoyance → Sleep**  | **0.010 (0.003, 0.019)a** | **0.003** |
| (7) LAeq → Annoyance → Sleep → PA | 0.00003 (-0.0001, 0.0003) | 0.535 |
|  |  |  |
| **NO2**  |  |  |
| Standardized total effect  | -0.042 (-0.116, 0.028) | 0.245 |
| Standardized direct effect  | -0.063 (-0.132, 0.003) | 0.063 |
| Standardized total indirect effect  | 0.021 (-0.002, 0.048) | 0.074 |
| Unstandardized specific indirect effects through: |  |  |
| (8) NO2 → Annoyance | 0.001 (-0.0002, 0.005) | 0.111 |
| (9) NO2 → Annoyance → RQ → SC | 0.00002 (-0.00002, 0.0002) | 0.253 |
| **(10) NO2 → Annoyance → RQ → PA** | **0.00003 (0.000001, 0.0001)a** | **0.034** |
| (11) NO2 → Annoyance → RQ  | 0.0001 (-0.00004, 0.0005) | 0.218 |
| (12) NO2 → Annoyance → SC  | 0.0001 (-0.0001, 0.001) | 0.293 |
| (13) NO2 → Annoyance → Sleep  | 0.003 (-0.0003, 0.008) | 0.076 |
| (14) NO2 → Annoyance → Sleep → PA | 0.00001 (-0.00004, 0.0001) | 0.461 |

Abbreviations: GHQ – General Health Questionnaire, LAeq – day equivalent noise level, NO2 – nitrogen dioxide, PA – physical activity, RQ – restorative quality, SC – social cohesion. aCoefficient is statistically significant at p < 0.05.

*3.4. Bidirectional association between environmental annoyance and GHQ*

The non-recursive nested Model 2 produced almost identical fit indices as Model 1: χ2 (422) = 821.348, p < 0.001; CFI = 0.941; RMSEA = 0.036 (90% CI: 0.033, 0.040); SRMR = 0.044; AIC = 1033.348; BCC = 1043.546. Chi-square difference was ∆χ2 (2) = 4.227, which was below the critical value (5.99) for 2 *df* and p ≤ 0.05. These results suggested that the addition of the reciprocal path between GHQ and environmental annoyance did not significantly improve the model fit. Moreover, the standardized coefficient for the path “annoyance → GHQ” (β = 0.663; 95% CI: -0.012, 1.893; p = 0.055) was appreciably larger than the coefficient for the reciprocal path “GHQ → annoyance” (β = 0.120; 95% CI: -0.064, 0.291; p = 0.193).

**4. Discussion**

*4.1. Overall findings*

This study examined associations between residential noise and air pollution and mental ill-health in a sample of Bulgarian students. We observed an association between higher LAeq and poorer mental health. Environmental annoyance and neighborhood restorative quality emerged as key factors in the serial mediation chain. The association for NO2 wasonly indirect. To our knowledge, we are the first to test such a comprehensive conceptual model in an attempt to expand our rudimentary understanding of the mediators underlying observed associations and how they may work together.

*4.2. LAeq*

Tests of the Crude linear regression model indicated that LAeq was associated with mental health. That is consistent with previous studies that focused on other aspects of mental ill-health (cf. Tzivian et al., 2015). To name a few examples, a seminal cohort study by Stansfeld et al. (1996) did not find an association between noise and overall psychiatric disorder, yet there was suggestive evidence that it may contribute to anxiety. More recently, Orban et al. (2016) reported higher risk of depressive symptoms in people exposed to over 55 dB(A) for 5 years, and Generaal et al. (2018) reported higher prevalence and severity of depression/anxiety in association with higher traffic noise.

In the model with multiple indirect paths, LAeq was associated with GHQ indirectly through higher annoyance, which in turn related to lower restorative quality, and in turn to lower physical activity, and thus to poorer mental health. Simultaneously, higher annoyance was related to higher sleep disturbance, and thereby to poorer mental health. That is in line with claims of van den Berg et al. (2014) that daytime noise annoyance is stronger associated with perceived noise-induced sleep disturbance than the actual noise level because people might transfer their daytime annoyance to the moment of conscious awakening at night. Residential noise was associated with lower restorative quality of the living environment, and thereby seemingly contributed to mental ill-health (cf. von Lindern et al., 2016). Our findings are congruent with those from our previous study in Plovdiv (Dzhambov et al., 2017), which expanded von Lindern et al.’s model by including physical activity and social cohesion as factors subsequent to restorative quality. However, unlike that previous study, social cohesion was not strongly associated with mental health in the present study, and thus we observed no serial mediation through it. Contrasting findings can be explained by differences in populations under study (youth *vs* young adults) or the shortened instruments used to measure social cohesion in the present study. In broader outline, our results concur with previous studies on related constructs. For instance, Héritier et al. (2014) found that the association between road traffic noise and health-related quality of life was mediated by annoyance and sleep disturbance. In another study (Urban and Máca, 2013), noise annoyance and residential satisfaction stood on the pathway linking noise exposure to life satisfaction.

*4.3. NO2*

There was no overall association between NO2 and GHQ, corroborating findings of some authors (e.g., Wang et al., 2014; Generaal et al., 2018). However, other studies suggested that particulate and gaseous pollutants may increase symptoms of depression/anxiety (e.g., Lim et al., 2012; Power et al., 2015). Noteworthy, majority of previous studies in the field sampled middle-aged or elderly participants; therefore direct comparison with our findings is hindered. Moreover, they did not use the GHQ.

For mediation to exist, there is no requirement that there be evidence of a total effect of exposure on outcome (Hayes, 2013; Zhao et al. 2010). In SEM, NO2 was indirectly associated with GHQ through higher annoyance, which in turn was associated with lower restorative quality, and thus with lower physical activity. This is in line with the observation by von Lindern et al. (2016) that air pollution could make the neighborhood environment less appealing settings for outdoor recreation, thereby hampering restoration from other daily stressors, and thus leading to diminished mental health. Ours is the first study to replicate those findings and specify serial mediation paths through physical activity, social cohesion, and sleep disturbance. As for the marginally significant mediation through annoyance and sleep disturbance, if it represents a non-spurious indirect path, it could be due to NO2 acting as a proxy for traffic intensity and vibration or to the cognitive stress caused by air pollution, which may promote non-specific health symptoms (cf. Stenlund et al., 2009).

*4.4. Association between GHQ and environmental annoyance*

 It has been theorized that the association between mental health and some of the examined mediators may go both ways because people with poor mental health may be more vulnerable to environmental stressors (van Kamp et al., 2013). In the present study, annoyance mediated the association between LAeq and GHQ, but not the other way around. The path linking annoyance to GHQ was associated with an appreciably larger regression weight than the reciprocal path. Given that we relied on cross-sectional data, these findings should be taken with caution. Still, it is reassuring that they are somewhat paralleled by a recent longitudinal study on the population living near Frankfurt airport (Schreckenberg et al., 2017). Schreckenberg et al. (2017) observed that, despite a bidirectional association between noise annoyance and mental well-being, the effect of poor mental health on annoyance was independent from sound exposure, that is, the indirect effect of noise via annoyance was considerably higher than the mediation effect of mental well-being.

*4.5. Stratified results*

 Stratified analyses indicated that both LAeq and NO2 were stronger associated with GHQ in non-Bulgarians. No previous study in the field has tested for modification by ethnicity, therefore no comparison is possible. Importantly, non-Bulgarians (who were mostly students from the United Kingdom) were much more likely to spend ≥ 8 hours/day at home. Therefore, the stronger correlation with GHQ might be due to the fact that residential LAeq and NO2 better represented their personal exposure. LAeq also was stronger associated with poor mental health in those living at their current address for less than 5 years, and that association can also be attributed to the fact that foreigners had moved to Plovdiv recently. There might be multiple explanations for the stronger effect of NO2 in men, such as differences in the way they use community amenities.

*4.6. Strengths and limitations*

 The rich data and use of validated measures enabled us to operationalize multiple intertwined pathways linking residential noise and air pollution to mental ill-health. To our knowledge, this is the most comprehensive model so far. Also, the joint effect of noise and air pollution has rarely been addressed in the previous research (Tzivian et al., 2015). We sampled much younger participants compared to previous studies that focused on middle-aged or elderly participants (Tzivian et al., 2015). Also, we had a high response rate (> 80%). We were able to reduce residual confounding (by environmental noise and air pollution on campus) by focusing on students from one university, where students spent most of their time when not in their neighborhood.

 However, we acknowledge several limitations. First, this study is cross-sectional, which precludes us from drawing causal inferences about some observed associations. Although it is much more likely for objectively-measured noise and air pollution to cause poor mental health than the other way around, associations between perceived variables may go both ways. As already noted, participants with poor mental health may have tendency to complain more about their environment and spend less time outdoors engaged in physical activity and social interactions. We did test for a reciprocal association between the centeal mediator, annoyance. and mental health, but the cross-sectional non-recursive SEM approach does not yield exactly the same estimates as a true cross-lagged effects model, for which it is only an approximation (Wong and Law, 1999). Moreover, our model was theoretically underidentified because some factors (e.g., LAeq, sex, income) were allowed to relate to both annoyance and GHQ, and thus the parameters estimated from this model could be questionable (cf. Wong and Law, 1999). Therefore, the adequacy of our conclusions about the relation between annoyance and mental ill-health should be confirmed in a longitudinal study, which has been planned in a subsample of our participants.

In order to keep our model parsimonious, we did not test for all plausible associations between the factors in it. For example, perceived sleep disturbance is highly correlated with noise annoyance (van den Berg et al., 2014); therefore, there may be a bidirectional association between them. Also, poor sleep may engender chronic tiredness and subsequent reduced cognitive function (Killgore, 2010), which could have a detrimental effect on residents’ perception of the local environment, and thus reduce its perceived restorative quality.

 Young adulthood was of particular interest given that most disorders begin during that period (Patel et al., 2007). The student occupation was also of itself interesting – being a student is commonly experienced as highly stressful, chronic stress is likely to increase the risk of some underlying disorder, and the GHQ screens for this risk with items that tap chronic stress. However, our sample was from a very specific setting (i.e., medical school), so it was not representative of all young adults in Plovdiv. The internal validity of our study should still be high though because we controlled for a wide range of sociodemographic and residential factors.

 Because this was a re-analysis of data collected to study the mental health benefits of natural environments, we did not collect data on noise sensitivity, which is an influential predictor of noise annoyance and mental health (Stansfeld, 1992). Also, to reduce questionnaire length and response burden, we used a reduced number of items from the PRS and PNSC-BF to describe restorative quality and social cohesion.

We only considered the daytime LAeq indicator, but alternative noise indicators for exposure to multiple sound sources may perform better and yield stronger exposure-response relationships in noise and health research (Lercher et al., 2012; Lercher et al., 2018). We also had no information on indoor noise exposure (e.g., from neighbors), which was considered in the annoyance questionnaire. Reassuringly, LAeq was similarly correlated with traffic noise annoyance (r = 0.17), noise annoyance from other neighborhood sources (r = 0.11), and vibration annoyance (r = 0.12), which suggests that people’s perceptions may be intertwined, or simply that areas with higher traffic volume were more noisy in general. Further, it is possible that we have overestimated noise exposure at addresses located on minor roads and in the suburbs, owing to the limited observed range of measurements used to construct the LUR. NO2 data were not of best quality either (i.e., the LUR model was global, not developed specifically for our study area, and was based on relatively few monitor stations in Bulgaria), which could explain the rather weak correlations with other variables.

 Finally, data were collected in October – November, when people spend less time outdoors than in summer. By adjusting for month, we controlled for monthly variation in noise annoyance (cf. Brink et al., 2016). Owing to these limitations, the associations we found are likely underestimated and lend further support to our hypothesis.

**5. Conclusion**

We observed an association between higher residential noise and poorer mental health. Environmental annoyance and neighborhood restorative quality emerged as key mediators. First, noise exposure was associated with higher annoyance, and through it with lower neighborhood restorative quality, and in turn with lower physical activity, and thus with poorer mental health. Second, higher annoyance was associated with higher sleep disturbance, and in turn with poorer mental health. Air pollution was associated with mental ill-health only indirectly through higher annoyance, lower restorative quality, and lower physical activity working in serial.

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**Conflicts of interests**

We declare no actual or potential conflicts of interests. This study received no external funding.

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