Environment International 143 (2020) 105960

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

The independent association of source-specific transportation noise exposure, noise annoyance and noise sensitivity with health-related quality of life

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ARTICLE INFO

Keywords:
Noise
Aircraft
Railway
Road traffic
Annoyance
Sensitivity
Health-related quality of life

ABSTRACT

Noise exposure is affecting health-related quality of life (HRQoL). There are many modelling approaches linking specific noise sources with single health-related outcomes. However, an integrated approach is missing taking into account measured levels as well as noise annoyance and sensitivity and assessing their independent association with HRQoL domains. Therefore, we investigated the predictive association of most common transportation noise sources (aircraft, railway and road traffic) as well as transportation noise annoyance and noise sensitivity with HRQoL using data from SAPALDIA (Swiss Cohort Study on Air Pollution and Lung and Heart Diseases in Adults).

We assessed 2035 subjects, who participated in the second and third wave of SAPALDIA (3&4) and had complete information on exposure, outcome and covariates. At SAPALDIA3, we calculated annual means (Lden) of source-specific transportation noise exposure at the most exposed facade of participant's dwelling floor height. Participants reported noise annoyance on the widely used 11-point ICBEN scale and answered to 10 questions assessing individual noise sensitivity. To assess the potentially predictive effect of these noise exposures, HRQoL was assessed about 8 years later (SAPALDIA4) using the SF-36. We performed predictive multiple quantile regression models to elucidate associations of noise parameters measured at SAPALDIA3 with median SF-36 scores at SAPALDIA4.

Source-specific transportation noise exposures showed few yet not consistent associations with HRQoL scores. We observed statistically significant negative associations of transportation noise annoyance with HRQoL scores covering mental health components (adjusted difference in SF-36 mental health score between highest vs. lowest annoyance tertile: −2.54 (95%CI: −3.89; −1.20). Noise sensitivity showed strongest and most consistent associations with HRQoL scores covering both general and mental health components (adjusted difference in SF-36 scores between highest vs. lowest sensitivity tertile: Mental health −5.96 (−7.57; −4.36); general health −5.16 (−7.08; −3.24)).

Abbreviations: HRQoL, Health-related quality of life; SAPALDIA, Swiss Cohort Study on Air Pollution and Lung and Heart Diseases in Adults; SF-36, 36-Item Short-Form Health Survey; CI, Confidence interval; dB, Decibel; PCS, physical component scores; MCS, mental component; PF, physical functioning; BP, bodily pain; GH, general health perception; VT, vitality; MH, mental health perception

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https://doi.org/10.1016/j.envint.2020.105960
Received 30 March 2020; Received in revised form 10 June 2020; Accepted 5 July 2020

Within all noise parameters, we predominantly observed negative associations of noise sensitivity with HRQoL attaining a magnitude of potential clinical relevance. This implies that factors other than transportation noise exposure may be relevant for this exposure-outcome relation. Nonetheless, transportation noise annoyance showed relevant associations with mental health components, indicating a negative association of transportation noise with HRQoL.

1. Introduction

Noise has globally become one of the most common environmental exposures and has been included by the WHO in the first priority list of environmental stressors influencing public health (WHO, 2011). The rapid growth of populations is increasing the demand for aircraft, road and railway transportation while decreasing available space per citizen (Kotzeva and Urban, 2016). Hence, minimizing excessive noise exposure has become a major aspect for urban development and planning policies (Jarosińska et al., 2018).

Exposure to noise - also referred as unwanted or harmful sound - shows adverse effects on physiological and psychological health outcomes (Hanninen et al., 2014). Recent research has demonstrated that environmental noise exposure may increase the risk of hypertension, stroke and ischemic heart disease (Van Kempen et al., 2018), decrease physical activity (Foraster et al., 2016), promote obesity (Oftedal et al., 2015; Pyko et al., 2015; An et al., 2018; Foraster et al., 2018), increase the risk for type 2 diabetes (An et al., 2018; Eze et al., 2017; Sørensen et al., 2013), and possibly also relate to anxiety and depression (Clark and Paunovic, 2018; Dzhambov and Lercher, 2019;16).

Studies on the association of transportation noise exposure with HRQoL have found mixed results. A recent systematic review identified 20 studies on the association of transportation noise exposure with HRQoL in adults. Ninety percent of these studies were cross-sectional and only three studies looked at mutually adjusted co-exposures of noise sources (aircraft, railway and road traffic) (Clark and Paunovic, 2018). Most studies used LAeq noise metrics and less than half of the studies used Lden. Further, most studies tended to make poor adjustments for the individual perception and ability to cope with higher noise levels. These personal factors are captured in both noise annoyance (a measure of the grade of disturbance and dissatisfaction from noise exposure (Guski, 1999)), and in noise sensitivity (a measure of the individual variation in perception of noise effects (Smith, 2003)) making it difficult to disentangle the effects of noise on HRQoL. A further study elucidated the relationship of source-specific transportation noise and transportation noise annoyance with HRQoL, yet did not consider noise sensitivity (Héritier et al., 2014).

In addition to noise exposure itself, noise annoyance may be influenced by personal factors such as age and health status, the ability to cope with stress, the duration, frequency and source of exposure as well as noise sensitivity, which is probably the most important non-acoustic factor influencing noise annoyance (Fig. 1) (Urban and Máca, 2013). Furthermore, it was shown that different sources of transportation noise (aircraft, railway or road traffic) were related to different noise annoyance ratings at the same decibel level (dB) (Brink et al., 2019). Although the correlation of noise sensitivity and noise annoyance is well-established (Urban and Máca, 2013; Okokon et al., 2015; Shepherd et al., 2010), noise sensitivity is invariant across noise exposure levels (Belojevic et al., 2003; Zimmer, 1999). Noise sensitivity, a measure for the individual perception of a given level and quality of noise, is seen as an aspect of personality. The impact of noise sensitivity on annoyance ratings is fairly remarkable as it can lower thresholds of annoyance up to 10 dB. Higher noise annoyance and sensitivity ratings were generally associated with lower HRQoL scores, but these studies did not consider source-specific noise exposure (Shepherd et al., 2010; Shepherd et al., 2016; Welch et al., 2018; Dratva et al., 2010).

To the best of our knowledge, few studies have investigated the triangular relationship of source-specific noise levels, transportation noise annoyance and noise sensitivity (Fyhri and Aasvang, 2010; Fyhri and Klæboe, 2009), yet no study has investigated these parameters in

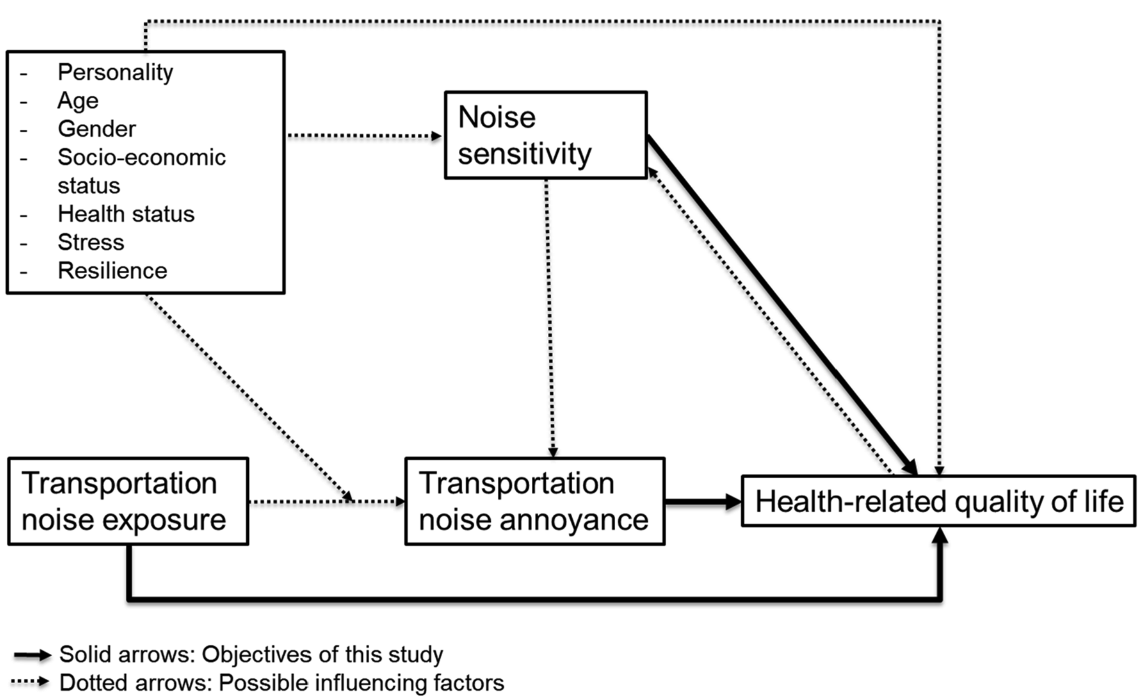

Fig. 1. Hypothesized pathways of transportation noise annoyance, noise sensitivity and source-specific transportation noise exposure with health-related quality of life.

independent and joint associations with HRQoL in the same population. A combined investigation of these factors will help minimize oversimplification of the relationship between transportation noise and HRQoL (Clark and Paunovic, 2018). Therefore, the objective of this study was to investigate the independent association of source-specific transportation noise levels (aircraft, railway and road traffic), noise annoyance and noise sensitivity with HRQoL in a predictive longitudinal manner. Specifically, our main hypothesis was that the three mentioned noise parameters show direct associations with HRQoL, while transportation noise annoyance may be influenced by noise sensitivity and noise exposure and noise sensitivity as well as the latter mentioned pathway may be influenced by several subject-related factors. These factors are also directly associated to HRQoL and there might be an issue of reverse causality in the association of noise sensitivity and HRQoL (Fig. 1).

2. Materials and methods

2.1. Study population

The current research used data from SAPALDIA (Swiss Cohort Study on Air Pollution and Lung and Heart Diseases in Adults), a population-based cohort with associated biobank initiated in 1991. In the baseline assessment SAPALDIA1, 9′651 adults (18-62 years) were randomly recruited from eight study areas in Switzerland representing the country's geographic and cultural diversity (Martin et al., 1997). So far, three follow-ups were carried out including 8′047 subjects in SAPALDIA2 (2001/2002) (Martin et al., 1997), 6′088 in SAPALDIA3 (2010/2011) (Endes et al., 2017) and 5′189 in SAPALDIA4 (2017/18). Assessments and information obtained comprised among others, transportation noise modelling at residential addresses, multiple self-administered questionnaires (including items on noise annoyance, noise sensitivity and HRQoL) and health examinations of extended phenotypes over time. High-quality noise data, predicted at address and floor of residence and covering residential history, was available for SAPALDIA2 and SAPALDIA3. Noise annoyance data was available for SAPALDIA1-4, while noise sensitivity data was available only for SAPALDIA3. HRQoL data was available for SAPALDIA2-4. For the present study, we included 2035 participants who had complete information on source-specific transportation noise levels, transportation noise annoyance, noise sensitivity, HRQoL and relevant covariates. This allowed the investigation of the predictive association of noise level, transportation noise annoyance, and noise sensitivity at SAPALDIA3 with HRQoL at SAPALDIA4 (main model). A subset of these participants who also participated in SAPALDIA2 (n = 1835) were used to assess stability of findings (for transportation noise levels and transportation noise annoyance) over a longer period (Robustness models, SAPALDIA2-4) (Fig. 2).

The SAPALDIA cohort study complies with the Declaration of Helsinki. At each survey, the regional ethics committees granted ethics approval and participants provided written informed consent prior to participation.

2.2. Outcome measure - Health-Related quality of life (HRQoL)

HRQoL was assessed using the 36-Item Short-Form Health Survey (SF-36), a widely used HRQoL assessment tool, which was validated in large population-based surveys as well as in clinical settings (Hart et al., 2015; Keller et al., 1998). The questionnaire provides a summary of physical component scores (PCS) and mental component scores (MCS),

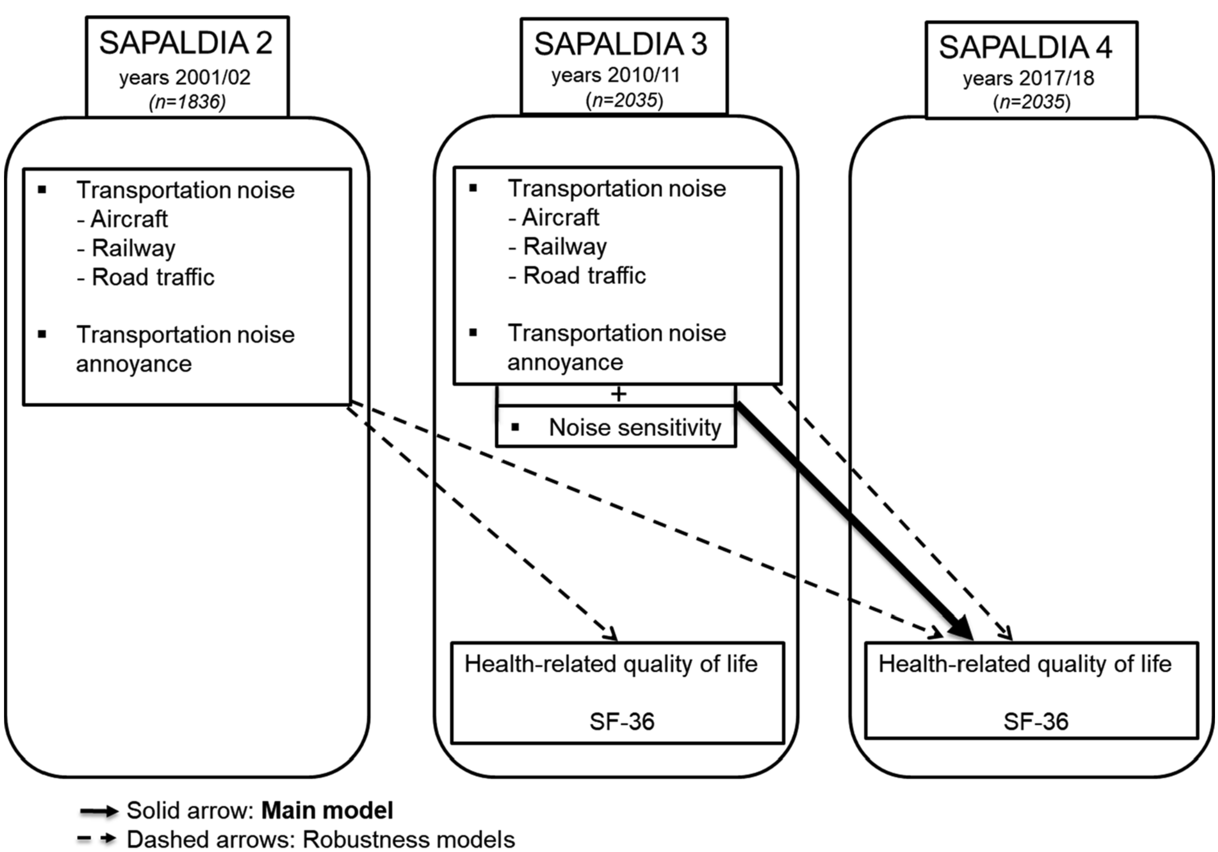

Fig. 2. Investigated variables at each SAPALDIA survey. *In the main model (solid arrow), the predictive association of noise (measured exposure; noise annoyance; noise sensitivity) at SAPALDIA3 on health-related quality of life at SAPALDIA4 was tested. In the context of 3 separate robustness models (dashed arrows) the predictive association of noise (measured exposure; noise annoyance) with health-related quality of life was tested for SAPALDIA2 to SAPALDIA3; SAPALDIA3 to SAPALDIA4 and SAPALDIA2 to SAPALDIA4.*

based on eight domains. The PCS comprises physical functioning (PF), bodily pain (BP), role-physical (RP) and general health perception (GH). The MCS reflects vitality (VT), social role functioning (SF), role emotional (RE) and mental health perception (MH). Scores for each subscale range from 0 to 100, and higher scores indicate better HRQoL (Framework, (SF-36). 1992).

Three domains of the SF-36 (social role functioning, role-physical & role emotional) had only very few distinct values in our sample and the proportion of subjects with the perfect score 100 was between 72% and 83%. Due to these ceiling effects and non-normal distributions, these domains were not considered in our analyses. As these variables represent minor sub-scales of the SF-36, their exclusion will still allow us to assess MCS and PCS as HRQoL outcomes.

2.3. Transportation noise exposure measurements

Aircraft, road and railway noise exposure at the residential address was estimated as annual mean day-evening-night levels (Lden, with respective 5 dB and 10 dB penalties for evening and night) for 2001 and 2011 (equivalent to the time points of SAPALDIA 2 and 3) using standardized Swiss-wide noise models as previously described in detail (Karipidis et al., 2014). The estimates were made at the most exposed facades on the participant's residential floors. Aircraft noise exposure was calculated using the FLULA2 model, which includes data on air traffic statistics and flight tracks based on radar data for the major Swiss airports (Thomann et al., 2005). Road traffic noise was derived by combining the Swiss sonROAD emission model (Heutschi, 2004) with the sound propagation model of StL-86 (Strassenlärm, 1987). The input data used for these models covered bridges, noise barriers as well as precise traffic statistics. Railway noise exposure was generated using the sonRAIL emission model (Thron and Hecht, 2010) and the propagation part of SEMIBEL (SEMIBEL, 1990). Input data considered railway tracks geometry, noise barriers, train type and data on rail traffic. The exposure modelling was validated with field measurements at sleeping and/or living room windows with sound level meters for one week, at locations primarily exposed to road traffic noise. The comparison of measured vs. calculated exposure levels resulted in a mean difference of the Lden of 1.6 ± 5 dB. The tendency to overestimate the exposure in the modelling was primarily caused by noise mitigation measures not considered in the modelling (Schlatter et al., 2017). Noise exposures were truncated to 30 dB for aircraft and railway noise and 35 dB for road traffic noise. Following our previous source-specific noise exposure studies (Foraster et al., 2018; Eze et al., 2017; Eze et al., 2018), these binary truncation indicators for aircraft and railway noise were added to the statistical models as covariates. As described by Vienneau, Héritier (Vienneau et al., 2019) "prior to epidemiological analyses, noise levels for all exposure definitions were censored at 35 dB for road noise and at 30 dB for railway and aircraft noise. This was done to account for background noise from diffuse sources in this lower range of exposures." Only a minor proportion of subjects (9%) were assigned truncated exposure, thus the truncation indicator for road traffic noise was not included in the models. The spearman correlation (Table A1) shows that the source-specific transportation noise Lden are correlated with the night variables (Leq), which gave us reason just to consider the Lden variables for our models.

2.4. Noise sensitivity and transportation noise annoyance

Noise sensitivity was assessed at SAPALDIA3 using the 10-item Weinstein's noise sensitivity scale, the psychometric properties of which have been previously reported (Weinstein, 1978a,b). Transportation noise annoyance was assessed at SAPALDIA2 and SAPALDIA3 using the 11-point numeric rating scale recommended by ICBEN (Fields et al., 2001). The specific questions used to assess noise sensitivity and transportation noise annoyance are presented in Table 1. The distribution of noise sensitivity and noise annoyance in the included participants are shown in Figs. A2 and A3.

2.5. Covariates – Confounders and effect modifiers

We selected individual and contextual potential confounders based on prior knowledge for inclusion in our models. These included participants' age (years), sex (male/female), years of formal education ($\leq 9/>9–12/>12$), smoking status (never/former/current), alcohol consumption ($\leq 1/>1$ glass per day), moderate-to-vigorous physical activity ($<150/\geq 150$ min per week) and body mass index (BMI; kg/m^2). On the contextual level, we included study area, neighborhood socioeconomic status (an index of Swiss socioeconomic position (SSEP)) based on the 2000 census data covering education and occupation of households members as well as room occupancy and rents of households in a neighborhood (Panczak et al., 2012). We included greenness index (normalized differential vegetation index based on land surface reflectance) within a 500 m buffer around participants' residences calculated for 2014 (Vienneau et al., 2017). Furthermore, we included participants' residential outdoor nitrogen dioxide (NO_2) exposure levels, a marker of traffic-related air pollution and potential confounder of traffic noise (Tétreault et al., 2013; Héritier et al., 2019). Annual mean levels of NO_2 were modelled at SAPALDIA2 by regressing NO_2 field measurements against covariates comprising dispersion model estimates, land-use, traffic, seasonal and climatic variables (adjusted R^2

Table 1
Questions on transportation noise annoyance and noise sensitivity.

Noise variable	Question	Combined summary measure, mean (SD)
Noise sensitivity Scale (Response range:10–60)	On a scale from 1 to 6 state how much you disagree or agree with the following statements. (If you strongly disagree choose 1, if you strongly agree choose 6, if you are somewhere in between, choose a number between 1 and 6) No one should mind much if someone turns up his or her stereo full blast once in a while I am easily awakened by noise I get annoyed when my neighbours are noisy I get used to most noises without much difficulty Sometimes noises get on my nerves and irritate me Even music I normally like will bother me if I am trying to concentrate I find it hard to relax in a place that is noisy I am good at concentrating no matter what is going on around me I get angry with people who make noises that keep me from falling asleep or getting work done I am sensitive to noise	39.92 (11.0)
Noise annoyance 0–10 rating scale (Response range:0–10)	How much are you annoyed by transportation noise in your home when the windows are open?	1.9 (2.4)

of 0.8) (Sally Liu et al., 2012) and at SAPALDIA3 using area-specific land-use regression models (adjusted R^2 of 0.5–0.9) (Eeftens et al., 2016).

2.6. Statistical analyses

First, we described the characteristics of the study population, summarizing continuous variables as medians and interquartile ranges, and categorical variables as proportions. To elucidate possible descriptive differences of population characteristics to transportation noise annoyance and noise sensitivity we stratified these variables by interquartile range (low/high).

The approach for testing predictive associations of HRQoL with noise parameters is illustrated in Fig. 2. In the main model we tested the predictive association of noise exposure, transportation noise annoyance and noise sensitivity measured at SAPALDIA3 with HRQoL measured at SAPALDIA4. In the robustness models, we tested the predictive associations of noise exposure and noise annoyance with HQRoL from SAPALDIA2 to SAPALDIA3; from SAPALDIA3 to SAPALDIA4; and from SAPALDIA2 to SAPALDIA4.

In our main model, we applied predictive multiple quantile regressions to assess associations of noise parameters measured at SAPALDIA3 with SF-36 scores measured at SAPALDIA4 given the left-skewed distribution of the HRQoL measures (Fig. A1). We adjusted for potential individual-level and contextual confounders measured at baseline, including sex, age, education, smoking status, alcohol consumption, study area, neighborhood socio-economic position, physical activity, BMI, NO_2 and greenness.

In the main model, regression models of noise parameters on HRQoL were performed in separate and joint analyses. First, in a multi-exposure model, we assessed the independent association of all exposures with HRQoL. Second, we looked at the alteration of association between the noise parameters and HRQoL when adjusting for the co-exposure variables (transportation noise, transportation noise annoyance and noise sensitivity). Finally, in sensitivity analysis we assessed robustness of our findings on the association of HRQoL with source-specific Lden and transportation noise annoyance by testing various modifications of variables and models (including categorized variables continuously and interaction terms) with and without adjustment for baseline chronic illness and HRQoL.

In robustness analysis we also benefitted from data obtained on additional time points. We investigated the predictive association of noise exposure at SAPALDIA2 respectively with HRQoL at SAPALDIA3 and SAPALDIA4. As noise sensitivity data had not been obtained at SAPALDIA2 it was not possible to test the robustness of the HRQoL association with this parameter over time. Separate multi-exposure regression models were thus run for SAPALDIA 2–3, SAPALDIA 3-4 and SAPALDIA 2-4, each looking at baseline exposure time-points with predictive outcome time-points as illustrated in Fig. 2, adjusting for covariates at the respective baseline time-points.

We performed all analyses using Stata 15 (Stata Corporation, College Station, Texas) and considered associations as statistically significant at an alpha-level of 0.05.

3. Results

Characteristics of the participants included in the main model of noise exposure at SAPALDIA3 with HRQoL at SAPALDIA4 are presented in Table 2. Women and men were equally distributed among the study participants and were on average 57 years old. Nearly two third of participants (62%) reported having completed secondary school, middle school or an apprenticeship. Most subjects either never smoked or stopped smoking, did not consume alcohol on a regular basis and met the physical activity guidelines of the WHO. The values of exposure, outcome and covariates of the smaller sample included in the robustness analysis and considering data from the earlier follow up (SAPALDIA2) can be found in Table A2. Furthermore, the characteristics stratified by transportation noise annoyance (low/high) and noise sensitivity (low/high) can be found in Table A3.

Table 2
Exposure, outcome and covariates values of the study population for the main model.

Variables	SAPALDIA3 *(n = 2035)*
SF-36 Score (0–100), median (IQR)	
General Health	72 (62–82)*
Physical Functioning	95 (85–100)*
Bodily Pain	84 (62–100)*
Vitality	65 (55–75)*
Mental Health	80 (72–88)*
Role-Physical	100 (75–100)*
Role-Emotional	100 (100–100)*
Social Functioning	100 (88–100)*
Transportation noise exposure (Lden, dB), mean (SD)	
Aircraft (dB)	35.2 (6.6)
Road (dB)	54.6 (7.6)
Railway (dB)	34.8 (8.3)
Noise variables, mean (SD)	
Noise annoyance (0–10)	1.9 (2.4)
Noise sensitivity (10–60)	32.92 (11.0)
Covariates	
Age (Mean, SD)	57 (10.5)
Female, n (%)	1003 (49%)
Education, n (%)	
Low	50 (2%)
Middle	1254 (62%)
High	731 (36%)
Smoking Status, n (%)	
Never	898 (47%)
Former	725 (38%)
Current	282 (15%)
Alcohol consumption, n (%)	
Regularly	854 (42%)
Physical Activity Guidelines (WHO), n (%)	
Sufficiently active	1548 (76%)
BMI, mean (SD)	25.9 (4.5)
SSEP, mean (SD)	64.7 (9.5)
NO_2, mean (SD)	18.7 (7.9)
Greenness, mean (SD)	0.6 (0.1)

*Values of SAPALDIA 4.
Data are median (interquartile range) for SF-36 variables, mean and SD for continuous variables and number (percent) for categorical variables.
Education: Low = Primary School (≤9years), Middle = Secondary school, middle school or apprenticeship (> 9-≤12 years), High = Technical College or University (≥12 years).
Physical Activity Guidelines (WHO).
Inactive: < 150 min of MPA and < 75 VPA per week.
Sufficient: > 150 min of MPA or > 75 VPA per week.
BMI = Body Mass Index, SSEP: Index of Swiss socioeconomic position.

3.1. Results from main model

3.1.1. Predictive associations of transportation noise exposure, transportation noise annoyance and noise sensitivity (SAPALDIA3) with HRQoL (SAPALDIA4)

The results on the independent association of noise exposure, transportation noise annoyance and noise sensitivity at SAPALDIA3 with HRQoL at SAPALDIA4 (Table 3), showed negative associations of railway noise exposure with GH by −1.45 (95%CI: −2.54; −0.36) and VT by −1.57 (95%CI: −2.71; −0.43) points in score per 10 dB increase of Lden. We observed statistically significant negative associations of the highest tertile of noise annoyance with HRQoL, decreasing the scores of BP by −3.85 (95%CI: −7.03; −0.67), of VT by −2.84 (95% CI: −4.70; −0.67) and of MH by −2.54 (95%CI: −3.89; −1.20)

Table 3
Independent predictive association of transportation noise, noise annoyance, and noise sensitivity at SAPALDIA3 with SF-36 derived HRQoL domains at SAPALDIA4.

Noise parameters	GH Coef (95% CI)	PF Coef (95% CI)	BP Coef (95% CI)	VT Coef (95% CI)	MH Coef (95% CI)
Aircraft	0.17 (-2.14; 2.49)	−0.01 (−0.81; 0.80)	−2.77 (−6.22; 0.67)	0.78 (−1.46; 3.02)	0.89 (−0.71; 2.50)
Road	−0.07 (−1.18; 1.04)	0.27 (−0.27; 0.80)	0.89 (−0.84; 2.62)	−0.41 (−1.58; 0.76)	0.13 (−0.70; 0.97)
Railway	−1.45 (−2.54; −0.36)**	−0.37 (−1.07; 0.33)	−0.65 (−2.46; 1.16)	−1.57 (−2.71; −0.43)**	−0.76 (−1.88; 0.36)
Noise annoyance					
Low	Ref				
Medium	−1.37 (−3.12; 0.38)	0.19 (−0.56; 0.94)	−0.04 (−2.43; 2.35)	−0.83 (−2.79; 1.12)	−0.89 (−2.89; 0.53)
High	−0.73 (−2.55; 1.10)	0.03 (−1.06; 1.11)	−3.85 (−7.03; −0.67)**	−2.84 (−4.70; −0.98)**	−2.54 (−3.89; −1.20)***
Noise sensitivity					
Low	Ref				
Medium	−2.19 (−3.76; −0.62)**	−1.29 (−2.09; −0.50)**	−4.00 (−6.46; −1.54)**	−1.54 (−3.30; 0.23)*	−1.27 (−2.41; −0.14)**
High	−5.16 (−7.08; −3.24)***	−1.50 (−2.37; −0.62)**	−7.07 (−9.97; −4.17)***	−6.67 (−8.50; −4.83)***	−5.96 (−7.57; −4.36)***

*$p < 0.1$ **$p < 0.05$ ***$p < 0.001$.
Results were calculated by quantile regression model mutually adjusted for all exposure variables and adjusted for confounders and truncation measures for rail & aircraft noise exposure.
Associations of HRQoL with aircraft, road and railway are displayed per 10 dB Lden.
HRQoL at SAPALDIA 4: GH, General Health; PF, Physical functioning; BP, Bodily Pain; VT, Vitality; MH, Mental Health.
Confounders (SAPALDIA3): Sex, age, education, smoking status, alcohol consumption, study area, neighborhood Swiss index of socioeconomic position, physical activity guidelines, body mass index, NO_2, greenness.
Categorical variables represent tertiles.

points in scores. High noise sensitivity ratings constantly showed negative associations with all HRQoL domains demonstrating consistent dose-exposure trends.

3.1.2. Change in association of HRQoL with noise parameters (noise sensitivity, transportation noise annoyance and noise exposure) when adjusting for co-exposures

The correlation between aircraft, road traffic and railway noise exposure, transportation noise annoyance, and noise sensitivity is presented in Table A1.

The association of noise sensitivity with GH and MH remained materially unaltered when adding transportation noise annoyance to the model, while for PF, BP and VT the associations slightly decreased, but remained statistically significant (Table 4). By adding the source-specific noise exposures, the association of noise sensitivity with HRQoL increased again for all domains except PF. Having all exposures in the model (Table 3) did not substantially change the effect of noise sensitivity on HRQoL.

The associations between noise annoyance and HRQoL were somewhat more sensitive to adjustment. After adjustment for noise sensitivity, the effect of noise annoyance on GH decreased. However, the effects on the other domains remained consistent. Noise annoyance associations remained stable for most HRQoL domains when adding the transportation noise exposures, except for a slight increase of the negative association with BP.

As for the transportation noise exposures, when adjusting for transportation noise annoyance the association with HRQoL remained quite stable. While there was a tendency for noise annoyance to attenuate the negative association of GH and VT with railway noise, adding noise sensitivity had the opposite effect.

3.1.3. Association of HRQoL with noise sensitivity, transportation noise annoyance and transportation noise exposure measured as continuous variables, additionally adjusted for HRQoL, and considering effect modification

The associations of noise sensitivity, transportation noise annoyance, and source-specific transportation noise exposure measured at SAPAPLDIA3 with HRQoL at SAPALDIA4 were confirmed when applying the variables continuously (Table A4), and were not substantially altered by additionally adjusting analyses for HRQoL (Table A5) and chronic illness (Table A6) at baseline SAPALDIA3. Single pollutant models for each noise source in relation to HRQoL were similar to the mutually adjusted models (Table A7). Additionally, by adding interaction terms of the noise parameters with age, gender and education we observed no relevant effect modifications in the association of the noise parameters with HRQoL.

3.2. Results from robustness models

3.2.1. Consistency in the association of HRQoL with transportation noise exposure and transportation noise annoyance across three follow-ups (SAPALDIA2 2001 – SAPALDIA3 2011 – SAPALDIA4 2017)

In this somewhat smaller sample consisting of subjects participating in all three SAPALDIA follow-up examinations, we illustrated the mutually adjusted association of transportation noise exposure and transportation noise annoyance across three follow-up time-points of SAPALDIA in Fig. 3.

Aircraft noise showed a statistically not significant trend for a negative association with BP over the three follow-ups. Railway noise exposure showed little consistency in its association with domains of HRQoL when compared to the larger sample of the main model and across the different time points. In the smaller sample, there was a tendency for a consistent direction of association with PF and BP. The statistically significant negative associations with GH and VT were only observed in SAPALDIA3 – 4 and SAPALDIA 2 – 4, while the results of SAPALDIA 2 – 3 displayed the opposite. These differences across time points are not explained by differences in sample size, as the negative association of railway noise with GH and VT was observed in the reduced sample irrespective of adjustment for noise annoyance and sensitivity.

The negative association of transportation noise annoyance with HRQoL was observed to be stable in direction over the three follow-ups.

4. Discussion

This study examined the independent association of source-specific measured noise exposure, transportation noise annoyance and noise sensitivity with HRQoL in a predictive longitudinal setting. Among all the considered noise parameters, noise sensitivity exhibited the most consistent association with HRQoL and a clear dose–response trend. We also thoroughly investigated this association in joint and independent analysis and thereby addressed interrelations between the co-exposures.

Table 4
Change in predictive associations of noise sensitivity, transportation noise annoyance and noise exposures (SAPALDIA3) with HRQoL (SAPALDIA4), when adjusting for co-exposures.

	GH Coef (95% CI)	PF Coef (95% CI)	BP Coef (95% CI)	VT Coef (95% CI)	MH Coef (95% CI)
Noise sensitivity					
Low	Ref				
Medium	−1.93 (−3.55; −0.30)**	−1.37 (−2.14; −0.59)**	−4.53 (−6.61; −2.44)***	−2.64 (−4.46; −0.81)**	−1.87 (−3.24; −0.49)**
High	−4.95 (−6.76; −3.15)***	−3.53 (−2.53; −0.86)***	−8.01 (−10.54; −5.48)***	−7.43 (−9.34; −5.51)***	−6.68 (−8.44 ; −4.92)***
Noise sensitivity		+ ***transportation noise annoyance***			
Low	Ref				
Medium	−1.89 (−3.48; −2.29)**	−1.49 (−2.33; −0.66)***	−3.73 (−6.01; −1.44)**	−1.81 (−3.71; 0.10)*	−1.19 (−2.46; 0.08)*
High	−4.79 (−6.70; −2.88)***	−1.66 (−2.57; −0.75)***	−7.14 (−9.82; −4.46)***	−6.35 (−8.45; −4.25)***	−6.18 (−7.84 ; −4.51)***
Noise sensitivity		+ ***modelled road, railway and aircraft noise exposure***			
Low	Ref				
Medium	−2.42 (−3.89; −0.95)**	−1.25 (−2.03; −0.48)**	−4.04 (−6.52; −1.56)**	−2.17 (−3.91; −0.42)**	−1.86 (−3.10; −0.62)**
High	−5.35 (−7.23; −3.48)***	−1.61 (−2.48; −0.74)***	−8.03 (−10.74; −5.33)***	−7.34 (−9.24; −5.45)***	−6.64 (−8.29; −4.98)***
Noise annoyance					
Low	Ref				
Medium	−1.60 (−3.55; 0.35)	0.13 (−0.54; 0.80)	−0.52 (−2.68; 1.63)	−0.87 (−2.70; 0.94)	−1.10 (−2.45; 0.25)
High	−1.66 (−3.30; −0.02)**	0.01 (−1.08; 1.10)	−4.80 (−7.83; −1.77)**	−4.14 (−5.99; −2.30)***	−2.92 (−4.32; −1.52)***
Noise annoyance		+ ***noise sensitivity***			
Low	Ref				
Medium	−1.13 (−2.95; 0.68)	0.36 (−0.42; 1.14)	−0.56 (−2.88; 1.75)	−0.91 (−2.97; 1.14)	−1.38 (−2.87; 0.11)*
High	−0.83 (−2.57; 0.90)	0.16 (−0.95; 1.28)	−4.22 (−7.21; −1.24)**	−3.56 (−5.46; −1.58)***	−2.83 (−4.25; −1.42)***
Noise annoyance		+ ***modelled road, railway and aircraft noise exposure***			
Low	Ref				
Medium	−1.25 (−3.17; 0.67)	0.12 (−0.58; 0.83)	−0.53 (−2.55; 1.49)	−1.14 (−2.93; 0.65)	−1.08 (−2.48; 0.31)
High	−1.79 (−3.56; −0.01)**	0.18 (−0.89; 1.26)	−5.37 (−7.97; −2.77)***	−4.25 (−6.20; −2.31)***	−2.89 (−4.45; −1.33)***
Noise exposures					
Aircraft	1.04 (−1.24; 3.32)	−0.14 (−0.70; 0.41)	−2.32 (−5.78; 1.14)	0.19 (−1.83; 2.21)	0.07 (−1.58; 1.73)
Road	−0.66 (−1.77; 0.44)	0.24 (−0.22; 0.71)	0.52 (−0.70; 1.75)	−0.25 (−1.45; 0.95)	−0.10 (−1.00; 0.80)
Railway	−1.40 (−2.46; −0.35)**	−0.31 (−0.82; 0.20)	−1.30 (−3.59; 0.99)	−1.39 (−2.71; −0.08)**	−0.61 (−1.75; 0.53)
+ ***transportation noise annoyance***					
Aircraft	0.77 (−1.50; 3.04)	−0.15 (−0.95; 0.65)	−2.33 (−4.85; 0.19)*	1.09 (−0.81; 2.99)	0.80 (−1.07; 2.67)
Road	−0.22 (−1.34; 0.91)	0.23 (−0.31; 0.78)	1.11 (−0.31; 2.52)	0.05 (−1.08; 1.18)	0.52 (−0.41; 1.44)
Railway	−1.23 (−2.31; −0.14)**	−0.34 (−0.94; 0.27)	−0.09 (−1.99; 1.81)	−1.32 (−2.61; −0.03)**	−0.11 (−1.20; 0.98)
+ ***noise sensitivity***					
Aircraft	0.27 (−1.91; 2.47)	0.02 (−0.79; 0.82)	−2.70 (−5.72; 0.32)*	0.24 (−2.18; 2.66)	0.18 (−1.51; 1.86)
Road	−0.26 (−1.277; 0.76)	0.32 (−0.23; 0.86)	0.42 (−1.09; 1.94)	−0.99 (−2.10; 0.11)*	−0.24 (−1.12; 0.64)
Railway	−1.67 (−2.71; −0.63)**	−0.39 (−0.98; 0.20)	−1.22 (−3.06; 0.62)	−1.66 (−2.67; −0.65)**	−0.86 (−1.95; 0.22)

*p < 0.1 **p < 0.05 ***p < 0.001.
Results were calculated by quantile regression model adjusted for confounders and truncation measures for rail & aircraft noise exposure.
Associations of HRQoL with aircraft, road and railway are displayed per 10 dB Lden.
HRQoL was assessed using the SF-36 at SAPALDIA 4: GH, General Health; PF, Physical functioning; BP, Bodily Pain; VT, Vitality; MH, Mental Health.
Confounders (SAPALDIA3): Sex, age, education, smoking status, alcohol consumption, study area, neighborhood Swiss index of socioeconomic position, physical activity guidelines, body mass index, NO_2, greenness.
Categorical variables represent tertiles.

4.1. Noise sensitivity

The predictive association of noise sensitivity was notable for both the PCS and MCS domains of the SF-36, and was insensitive to adjustments, categorization and adjustment for HRQoL at baseline (Table A5). The coefficients on the sub-scales GH, BP, VT and MH even surpassed 5 points in effect scores, pointing to the clinical relevance of the observed associations (Maruish, 2011). The values of noise sensitivity followed a Gaussian distribution, which indicate no clear cut-offs for individuals being sensitive or not (Fig. A2). The same distribution and data characteristics were found by studies in different settings (Okokon et al., 2015; Shepherd et al., 2010). Thus, the results suggest that at each level of noise sensitivity in the distribution, an increase in one score point increases the percentage of the population with a relevant reduction in HRQoL. Our results also add further evidence that noise sensitivity is invariant across noise exposure and annoyance levels as displayed in Table A1.

The study of Schreckenberg, Griefahn (Schreckenberg et al., 2010) only found an association of noise sensitivity and HRQoL domains covering physical health, while the study of Shepherd, Welch (Shepherd et al., 2010) and Stansfeld and Shipley (Stansfeld and Shipley, 2015) only found associations with mental health components. Our study found strong associations with both the PCS and MCS. However, as these are subjective measures of health states, it is possible that the physical health states are influenced by risk factors of mental health states, which would limit an absolute distinction between the two. We demonstrated that noise sensitivity seems to capture aspects related to future HRQoL that are independent of transportation noise annoyance and transportation noise exposure. Furthermore, our results are consistent with findings from Shepherd, Welch (Shepherd et al., 2010) and Stansfeld and Shipley (Stansfeld and Shipley, 2015) explaining that noise sensitivity seems being a relevant predictor of noise annoyance.

4.2. Transportation noise annoyance

Transportation noise annoyance was mainly related to MCS. Several studies share these results (Urban and Máca, 2013; Shepherd et al., 2016;13(8).; Dratva et al., 2010). This association proved to be robust

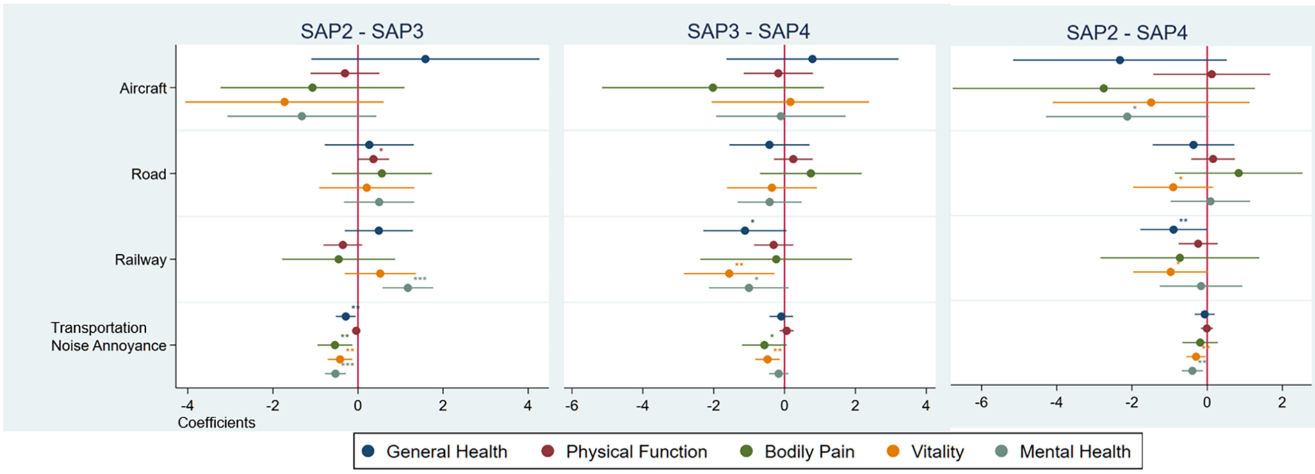

Fig. 3. Change in outcome, for the independent association of transportation noise exposure with HRQoL domains at different time points, including transportation noise annoyance.

throughout the three studied time-points (SAPALDIA2 −1991; SAPALDIA3 − 2001; SAPALDIA4 − 2017). Yet, after adjustment for the co-exposures - noise sensitivity and source-specific transportation noise exposures - the association slightly decreased and was less consistent than for noise sensitivity. Compared to noise sensitivity the values of transportation noise annoyance did not show a Gaussian distribution but instead were very right-skewed (Fig. A3). This indicates that most subjects reported not being annoyed by transportation noise. Furthermore, these findings underline that noise annoyance and noise sensitivity are capturing different concepts, despite the fact that the spearman's correlation revealed that transportation noise annoyance was correlated with railway noise and road traffic noise. This correlation has also been shown in other studies (Urban and Máca, 2013).

We can only speculate on the potential reasons for a less consistent association of noise annoyance with HRQoL compared to noise sensitivity. This may either point to the additional relevance of non-transportation noise (Shepherd et al., 2019; Park et al., 2018;13(8):; Dzhambov et al., 2017); to noise annoyance being more of an actual state response and noise sensitivity a personal trait response as well as to noise sensitivity reflecting non-noise related characteristics of participants (Shepherd et al., 2015; Park et al., 2017;17(1):; Shepherd et al., 2015) and personality given that the questions on noise sensitivity were not restricted to transportation noise. Among the hypothesized mechanisms underlying transportation noise annoyance and sensitivity with HRQoL, it is likely that an increase in stress hormones, like catecholamine and cortisol, is of relevance. Such an increase may subsequently lead to adverse health effects (Clark and Paunovic, 2018).

That both noise sensitivity and transportation noise annoyance showed negative associations with HRQoL implies that these noise measures may truly have significant impact on people's HRQoL. It is conceivable that noise annoyance and sensitivity are further influenced by poor health state itself. This bi-directional hypothesis is based on the fact that a degraded health state inhibits the individual response to life stressors, such as transportation noise (Schmidt and Klokker, 2014). Moreover, it was shown that especially adverse mental health states contribute to hypersensitivity and noise annoyance ratings (Tarnopolsky et al., 1978; Tarnopolsky et al., 1980). Fyhri and Klaeboe (Fyhri and Klaeboe, 2009) investigated the relationship of noise and health outcomes with the aim of finding causal directions. They did not find any relevant causal relationship; however, they recognized that noise sensitivity reflects vulnerability as it is also seen in subjects with adverse health states. Hence, their findings imply that noise sensitivity may not directly affect health but rather points together with health impairments to an enhanced vulnerability towards environmental stressors and health treats. This creates some reverse causation, which hinders causal inference regarding noise sensitivity. Our post-hoc finding of an association between baseline MH and follow-up noise sensitivity supports this notion (Table A8). Therefore, we cannot completely rule out the influence of reverse causation in our findings, despite the robustness of our models. Also noise sensitivity seems to be an independent predictor of transportation noise annoyance, being independent from actual noise exposure (van Kamp et al., 2004). The complex relationship of these noise variables is not fully elucidated, and warrants further investigation in future studies that also have longitudinal data on noise sensitivity, which is a limitation of our cohort.

4.3. Source-specific transportation noise (aircraft, railway and road traffic)

Among the source-specific noise exposures, we did not find any consistent association with HRQoL. It was only when predicting exposure at SAPALDIA3 to outcome at SAPALDIA4 that we found associations of railway noise exposure with the domains GH and VT. These associations were not confirmed at other time points. Nevertheless, the direction of our findings is in line with the recent systematic review of the WHO, stating that there could be a negative association of railway noise on QoL but that further investigations are needed to confirm this association (Clark and Paunovic, 2018). Consequently, we should adapt Fig. 1 and consider removing the line from transportation noise exposure to HRQoL, as this association remains unclear. However, most likely the absence of consistent associations of HRQoL with measured transportation noise, after adjustment for noise sensitivity and annoyance, rather suggests that noise exposure impacts HRQoL if combined with personality traits vulnerable towards the perception of noise and possibly other environmental stressors.

4.4. Strengths and limitations

Strengths of the current study comprise the longitudinal nature of the data, reaching a maximum of 20 years from exposure to outcome. Due to the rich data of this long lasting cohort, most known possible confounders and effect modifiers could be included in the models leading to minimization of biases. SAPALDIA is a general population sample for Switzerland, thus our findings are generalizable to the Swiss adult population. This study is the first to consider transportation noise exposure, transportation noise annoyance and noise sensitivity at the same time in analysis with HRQoL outcomes. The individually assigned noise exposure data covered all major transportation noise sources, and the included SAPALDIA participants are broadly distributed across the country in a mix of urban, suburban and rural areas. Information on transportation noise annoyance was asked in the same manner over the three follow-ups, while questions on noise sensitivity were added at the third follow-up.

Limitations of the study include the fact that information on noise sensitivity was only obtained at one time point of the follow-up, and no information on exposure to noise sources other than transport was available to differentiate between effects of noise annoyance and sensitivity from transport versus other sources. However, this might be a specific issue to the notion of noise sensitivity as it is not specific to transportation noise. We used the ICBEN scale for assessment on transportation noise annoyance. However, the question specifically asked for indoor transportation noise annoyance when the windows are open. Hence, we may not have captured overall transportation noise annoyance, yet our findings our consistent with other studies as shown previously. As demonstrated in post-hoc sensitivity analysis (Table A8), we cannot completely rule out reverse causation in our findings with noise sensitivity, especially for mental health, given that higher baseline MH score was associated with lower follow-up noise sensitivity. At the same time, the adjustments with baseline HRQoL (Table A6) did not materially alter the investigated relationships, indicating that the association of MH and noise sensitivity may not be entirely due to reverse causation.

Although we could have applied a more sophisticated statistical analysis in elucidating directionality, we have instead focused on a holistic approach of five HRQoL outcomes and numerous co-exposures and confounders to identify relevant trends and associations for further in-depth analysis. Future research should incorporate these aspects to further deepen our understanding of the underlying mechanisms linking these noise characteristics to HRQoL.

5. Conclusion

Our novel research findings point to noise sensitivity being inversely associated with physical and mental components of HRQoL in the general population. The observed size of associations are in a clinically relevant range. The more consistent associations with noise sensitivity compared to transportation noise annoyance suggest that sources other than transportation are relevant. We nevertheless also found transportation noise annoyance to be linked to lower scores of HRQoL covering mental health components. The inconsistency of independent associations with source-specific transportation noise suggest, from a HRQoL perspective that noise only if combined with personality traits vulnerable towards the perception of this environmental stressor, shows negative relations to HRQoL domains.

If additional longitudinal studies with repeat data on noise sensitivitiy confirm the strong predictive association of noise sensitivity with HRQoL, this finding should further strengthen and shape public health and clinical interventions to decrease noise exposure from all sources.

CRediT authorship contribution statement

Paco Cerletti: Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing. **Ikenna C. Eze:** Conceptualization, Methodology, Investigation. **Emmanuel Schaffner:** Data curation. **Maria Foraster:** Investigation. **Danielle Viennau:** Investigation. **Christian Cajochen:** Investigation. **Jean-Marc Wunderli:** Investigation, Validation. **Martin Röösli:** Investigation, Validation. **Daiana Stolz:** Investigation. **Marco Pons:** Investigation. **Medea Imboden:** Investigation, Project administration. **Nicole Probst-Hensch:** Funding acquisition, Project administration, Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors declare no conflict of interest.

Acknowledgement and funding

This work was supported by the Swiss National Science Foundation, SNF-SAPALDIA (grants numbers 33CS30-148470/1, 33CSCO-134276/1, 33CSCO-108796, 324730_135673, 3247BO-104283, 3247BO-104288, 3247BO-104284, 3247-065896, 3100-059302, 3200-052720, 3200-042532, 4026-028099, PMPDP3_129021/1, PMPDP3_141671/1); SNF-SiRENE (grant number CRSII3_147635) and the Swiss Federal Office for the Environment. SAPALDIA is also supported by the Federal Office of Public Health, the Federal Office of Roads and Transport, the cantonal government of Aargau, Basel-Stadt, Basel-Land, Geneva, Luzern, Ticino, Valais, and Zürich, the Swiss Lung League, the canton's Lung League of Basel Stadt/Basel Landschaft, Geneva, Ticino, Valais, Graubünden and Zurich, Stiftung ehemals Bündner Heilstätten, SUVA, Freiwillige Akademische Gesellschaft, UBS Wealth Foundation, Talecris Biotherapeutics GmbH, Abbott Diagnostics, European Commission 018996 (GABRIEL), Welcome Trust WT 084703MA.

The study could not have been done without the help of the study participants, technical and administrative support and the medical teams and field workers at the local study sites. MF is supported by a Beatriu de Pinós fellowship [2018/8374/I] awarded by the Universities and Research Secretariat of the Catalan Ministry of Business and Knowledge.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2020.105960.

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