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Long-term transportation noise annoyance is associated with subsequent lower levels of physical activity

Maria Foraster [a,b,*], Ikenna C. Eze [a,b], Danielle Vienneau [a,b], Mark Brink [c], Christian Cajochen [d], Seraina Caviezel [a,b], Harris Héritier [a,b], Emmanuel Schaffner [a,b], Christian Schindler [a,b], Miriam Wanner [e], Jean-Marc Wunderli [f], Martin Röösli [a,b], Nicole Probst-Hensch [a,b]

[a] Swiss Tropical and Public Health Institute, Socinstrasse 57, 4051 Basel, Switzerland
[b] University of Basel, Petersplatz 1, 4003 Basel, Switzerland
[c] Federal Office for the Environment, 3003 Bern, Switzerland
[d] Centre for Chronobiology, Psychiatric Hospital of the University of Basel, Wilhelm Klein-Strasse 27, 4012 Basel, Switzerland
[e] Krebsregister der Kantone Zürich und Zug, UniversitätsSpital Zürich, Vogelsangstrasse 10, 8091 Zürich, Switzerland
[f] Empa, Laboratory for Acoustics/Noise control, Swiss Federal Laboratories for Materials Science and Technology, Überlandstrasse 129, 8600 Dübendorf, Switzerland

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ABSTRACT

Noise annoyance (NA) might lead to behavioral patterns not captured by noise levels, which could reduce physical activity (PA) either directly or through impaired sleep and constitute a noise pathway towards cardiometabolic diseases. We investigated the association of long-term transportation NA and its main sources (aircraft, road, and railway) at home with PA levels. We assessed 3842 participants (aged 37–81) that attended the three examinations (SAP 1, 2, and 3 in years 1991, 2001 and 2011, respectively) of the population-based Swiss cohort on Air Pollution and Lung and Heart Diseases in Adults (SAPALDIA). Participants reported general 24-h transportation NA (in all examinations) and source-specific NA at night (only SAP 3) on an ICBEN-type 11-point scale. We assessed moderate, vigorous, and total PA from a short-questionnaire (SAP 3). The main outcome was moderate PA (active/inactive: cut-off ≥ 150 min/week). We used logistic regression including random effects by area and adjusting for age, sex, socioeconomic status, and lifestyles (main model) and evaluated potential effect modifiers. We analyzed associations with PA at SAP 3 a) cross-sectionally: for source-specific and transportation NA in the last year (SAP 3), and b) longitudinally: for 10-y transportation NA (mean of SAP 1 + 2), adjusting for prior PA (SAP 2) and changes in NA (SAP 3-2). Reported NA (score ≥ 5) was 16.4%, 7.5%, 3%, and 1.1% for 1-year transportation, road, aircraft, and railway at SAP 3, respectively. NA was greater in the past, reaching 28.5% for 10-y transportation NA (SAP 1 + 2). The 10-y transportation NA was associated with a 3.2% (95% CI: 6%–0.2%) decrease in moderate PA per 1-NA rating point and was related to road and aircraft NA at night in cross-sectional analyses. The longitudinal association was stronger for women, reported daytime sleepiness or chronic diseases and it was not explained by objectively modeled levels of road traffic noise at SAP 3. In conclusion, long-term NA (related to psychological noise appraisal) reduced PA and could represent another noise pathway towards cardiometabolic diseases.

1. Introduction

Long-term exposure to transportation noise has been associated with cardiovascular disease (Babisch, 2014; Dratva et al., 2012; van Kempen and Babisch, 2012; Vienneau et al., 2015), the leading cause of morbidity and mortality worldwide (Lozano et al., 2012; Murray et al., 2012), and could also relate to diabetes (Dzhambov, 2015) and obesity (Eriksson et al., 2014; Oftedal et al., 2015; Pyko et al., 2015). The major mechanism towards cardiovascular diseases may be through the direct physiological stress reaction to the actual level of noise during rest (i.e. direct pathway) (Babisch, 2002; Babisch et al., 2003; Basner et al., 2011; Münzel et al., 2014). A second mechanism relates to the psychological appraisal of noise through noise annoyance (i.e. indirect pathway). This is supported by a few studies that have observed associations between noise annoyance and cardiovascular diseases (Babisch et al., 2013; Ndrepepa and Twardella, 2011), however, little is known about the role of noise annoyance and its pathways towards chronic diseases.

Previous research has mostly regarded noise annoyance as a health-related outcome of well-being itself (World Health Organization, 1999). Noise annoyance leads to anger, disappointment, dissatisfaction,

Abbreviations: NA, noise annoyance; PA, physical activity.

* Corresponding author at: Department of Epidemiology and Public Health, Chronic Disease Epidemiology Unit, Swiss Tropical and Public Health Institute, Socinstrasse 57, Office location: Eulerstrasse 77, room: E706, 4051 Basel, Switzerland.
E-mail address: maria.foraster@unibas.ch (M. Foraster).

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withdrawal, helplessness, depression, anxiety, distraction, agitation or exhaustion, and sleep disturbance (World Health Organization, 1999). It has been also associated with decreased quality of life, including physical functioning (Dratva et al., 2010; Héritier et al., 2014; Shepherd et al., 2010). Both good quality and quantity of sleep and physical activity (PA) are crucial lifestyles and determinants of quality of life (Kim et al., 2015; Svantesson et al., 2015) and cardiometabolic diseases (Lee et al., 2012; Luyster et al., 2012; Svantesson et al., 2015). Therefore, although mostly related to acute reactions, repeated noise annoyance during the day and/or night could permanently change neurological signalling pathways in the brain (McEwen, 2008) and trigger chronic sleep and/or behavioral deregulations in the long-term which could impact PA performance and constitute an additional pathway to cardiovascular diseases but also to diabetes and obesity.

Furthermore, while the environment plays an important role on lifestyles such as PA (Brownson et al., 2009; Saelens et al., 2003), no studies so far have quantified the importance of specific ubiquitous factors such as noise. This is particularly relevant for noise annoyance, because the evidence indicates that the individual appraisal of noise, more than the noise level itself, contributes to a more attractive outdoor environment and promotes healthy habits (Tjeerd and Andringa, 2013; van Kempen et al., 2014).

Thus, we hypothesize that long-term noise annoyance may lead to lower PA either directly through decreased willingness to exercise or through impaired sleep quality and increased daytime sleepiness.

In a population-based sample of the well-characterized SAPALDIA (Swiss Cohort Study on Air Pollution And Lung and Heart Diseases In Adults) cohort, we aimed to evaluate the association of long-term transportation noise annoyance and its main sources at home with total, moderate, and vigorous PA, accounting for changes in annoyance. We also assessed potential effect modification by age, sex, body mass index, daytime sleepiness, noise sensitivity, and study area.

2. Materials and methods

2.1. Study sample

We assessed 3842 participants, 37 to 81 years of age, who attended the three examinations of the population-based Swiss Cohort Study on Air Pollution and Lung and Heart Diseases in Adults (SAPALDIA - The SAPALDIA Cohort, n.d.). The baseline study population was recruited in 1991 (SAP 1) and consisted of a random selection of 9651 adults aged 18–60 years from eight environmentally diverse areas in Switzerland (Martin et al., 1997). A total of 8047 participated in the first follow-up (SAP 2) in 2001–2003 (Ackermann-Liebrich et al., 2005) and 6088 participated in the second follow-up (SAP 3) in 2010–2011. Participants answered personal interviewer-administered questionnaires on socioeconomic, lifestyle, environmental, and health characteristics; and underwent cardiorespiratory measurements and provided blood. The latter contributed to a biobank for blood markers and genetics. A total of 4552 randomly-selected participants answered the longer versions of the main questionnaire at both follow-ups, which contained the information about PA. Information on general transportation noise annoyance was available at baseline and at the follow-ups (see Fig. 1). Source-specific noise annoyance was available at the second follow-up.

The study was approved by the ethics board of the eight SAPALDIA communities and all participants signed written informed consent.

2.2. Noise annoyance

Residential noise annoyance was reported on an ICBEN-type 11-point scale from 0 to 10. (Fields et al., 2001). General transportation noise annoyance in a 24 h period (from now on referred to "transportation noise annoyance") was collected at SAP 1, 2 and 3 as "*How much are you disturbed by transportation noise at home when windows are opened*?". Source-specific noise annoyance in the bedroom at night was reported only at SAP 3 as "*Thinking about the last 12 months, what number from 0 to 10 best shows how much you are bothered, disturbed or annoyed at home by the following potential noise sources during your regular sleeping hours*?"

We assessed the following sources of noise annoyance at SAP 3: a) "1-y road traffic noise annoyance", b) "1-y railway noise annoyance", c) "1-y aircraft noise annoyance" (the three at nighttime); as well as general annoyance: d) "1-y transportation noise annoyance (24 h)".

Since 1-y time windows might not be long enough to disentangle acute from chronic effects, we further evaluated longer-term means as the 10-y average of transportation noise annoyance between SAP 2 and SAP 1, available at all surveys. We discarded the 10-y average between SAP 3 and SAP 2, as it was highly correlated to the 1-y average at SAP 3, contained in the calculation (Spearman rank correlation, $r = 0.78$), therefore preventing any separation of the longer- and shorter-term effects. This also permitted the evaluation of noise annoyance previous to the outcome, in a longitudinal fashion. This strategy also allowed us to evaluate and control for the impact of changes in noise annoyance between visits, defined as the difference in annoyance rating between SAP 3 and 2. I.e. negative and positive values indicated reductions or increases in noise annoyance in SAP 3, respectively.

2.3. Outcomes

SAPALDIA collected information on PA at SAP 2 and 3 by means of four short questions related to the Swiss Health Survey ("Schweizerische Gesundheitsbefragung, 2012," 2014). The questions referred to the frequency, duration, and intensity of weekly exercise and allowed us to determine both the total amount of PA and its intensity, i.e. moderate or vigorous PA (See Appendix Table A.1 for translated wording of questions).

Our main analyses focused on PA levels (active/inactive) of two intensities (moderate and vigorous) at SAP 3: 1) Main outcome, moderate PA: the duration of moderate PA was asked in minutes. Participants were categorized as being active in moderate PA if they exercised for at least 150 min per week in a moderate intensity according to the PA guidelines (Lamprecht et al., 2014; World Health Organization, 2010). 2) Vigorous PA: the duration of vigorous PA was asked in categories (none, about 1/2 h, about 1 h, about 2–3 h, about 4–6 h, 7 h or more). To ensure that we met the vigorous PA recommendations of at least 75 min per week of vigorous intensity, and to increase the specificity, we took the cut-off category of ≥2 h, from now on ≥120 min/week, for being vigorously active.

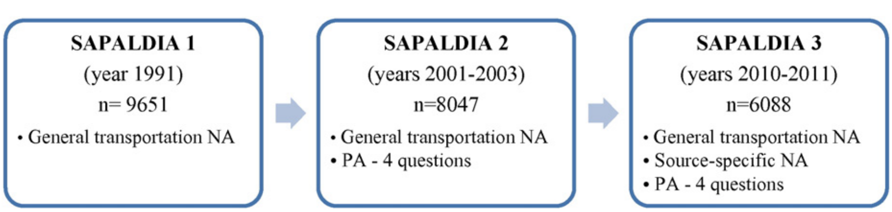

Fig. 1. Availability of information in SAPALDIA (SAP) about the outcome (physical activity: PA) and exposure (noise annoyance: NA) across the study period (baseline: SAP 1, follow-up 1: SAP 2, follow-up 2: SAP 3).

Finally, to evaluate the PA intensities in total, we defined total PA (active/inactive) also according to WHO. Participants were categorized as active if they were moderately and/or vigorously physically active or active for at least 150 min/week. The latter included any combination of moderate and twice the amount of vigorous PA (for this addition, categorical ranges of vigorous PA were averaged in minutes per week, e.g. "about 2–3 h" corresponded to 150 min/week).

2.4. Further data collection

We collected questionnaire-based data on potential confounders, effect modifiers, and mediators at SAP 3. This included age, sex, menopause (pre-, peri-, postmenopausal), cumulative educational level (low/middle/high), civil status (married/divorced/widowed/single), smoking (No/Yes), number of pack-years smoked, passive smoking (No/Yes), alcohol consumption (daily/weekly/rarely/never), consumption of raw vegetables, cooked vegetables, and fish (from 0 to 7 days/week), and study area. It also included health conditions such as hearing impairment (none/mild/severe), self-reported doctor-diagnosed depression or chronic diseases, including cardiometabolic diseases, asthma, and chronic bronchitis (at SAP 2 and 3), self-reported sleep deprivation after waking up (No/Yes), the Epworth daytime sleepiness score (0: none, 24: maximal) (Johns, 1991), and self-reported PA impairment in the last year due to cardiovascular problems. We also collected for the entire sample the Weinstein's noise sensitivity score item "*Are you sensitive to noise*?" from the 10-item Weinstein noise sensitivity score (Weinstein, 1980, Weinstein, 1978). We additionally accounted for a neighborhood-level socioeconomic index (deprivation index) from the census in year 2000 comprised of the median income, household occupancy, educational level, and occupation of the households' heads (Panczak et al., 2012). We used the measured height and weight to calculate body mass index (BMI) in kg/m^2.

2.5. Other environmental factors

We characterized environmental conditions at the geocoded residential addresses at SAP 3. Air pollution was assigned as a 1-y average of particulate matter of 10 μm diameter (PM_{10}) on a 200 × 200 m grid, based on the Swiss PolluMap Gaussian dispersion model of year 2010 (FOEN, 2013). Road traffic noise levels were assigned at the dwelling floor height for the most exposed façade as 1-y A-weighted equivalent noise levels over all 24 h (days) of the year (L_{24h}, in dB), based on a highly resolved model with comprehensive information about traffic characteristics, land-use and building heights, among others, as described elsewhere (Karipidis et al., 2014). We also linked residential distance (in meters) to major roads (i.e. streets with ≥5000 vehicles/day) based on the digital road network from the Swiss Federal Office of Topography (landscape model VECTOR25, year 2008) and the square kilometers of urban green areas and sport and leisure facilities (referred to as parks/leisure areas) in a 2000 m radius buffer around the home, available from the European Environment Agency hectare resolution dataset (CORINE CLC-2006 Version 13, 02-2010).

2.6. Statistical analysis

We performed descriptive analyses of all variables. Bivariate associations between the outcomes and exposures and of these two with all covariates were assessed with Spearman rank correlation (continuous variables), chi-square test (categorical variables), and Kruskal–Wallis test (continuous and categorical variables). We excluded participants with addresses that could not be geocoded at street level or with missing observations on the outcomes, exposures, and covariates of the main models ($n = 710$, 15.6%), resulting in 3842 cases with similar characteristics to all the interviewed participants ($n = 4552$) and all individuals having provided data at SAP 3 ($n = 6088$) (Appendix A, Table A.2).

We used multivariate mixed effects logistic regression to evaluate the association of each noise annoyance measure with the binary outcomes, and performed regression diagnostics. We considered two groups of analyses:

1) In cross-sectional analyses (SAP 3) we assessed the association of 1-y source-specific noise annoyance at night (i.e. road, railway and aircraft) as well as of 1-y transportation noise annoyance with PA. The 10-y average of transportation noise annoyance between SAP 2 and SAP 3 was highly correlated to the 1-y means and therefore not analyzed ($r = 0.78$). Longer-term time windows of exposure were analyzed at SAP 2 in the next step.
2) In longitudinal analyses (main model), we assessed the association of 10-y transportation noise annoyance (SAP 1 + 2) with PA at SAP 3, adjusting for the value of PA at SAP 2 and for the change in transportation noise annoyance between SAP 2 and 3. This model allowed a longitudinal comparison to better evaluate causality as well as to evaluate the impact of time windows longer than 1-y on PA, while also considering the impact and controlling for reported noise annoyance variations between assessments. This longitudinal approach with adjustment for the changes was possible given the moderate correlation ($r = -0.41$) of both annoyance factors. Finally, we evaluated the linearity of association 2) by using thin plate smooth splines.

Based on literature and hypothesized confounding, all models were consecutively adjusted for the following covariates obtained at the same time point as the outcomes (SAP 3): a) age, sex; b) menopause; c) educational level, civil status, alcohol consumption, smoking status, pack-years smoked, passive smoking, diet, BMI; d) a random effect by study area, to control for clustering of unobserved individual characteristics within areas. Further adjustments provided very similar effect estimates (Appendix, Table A.3) and were not considered for parsimony and to increase statistical power. This included additional adjustment of the main model for the size of parks/leisure areas and/or noise levels (to evaluate the subjective noise annoyance) and air pollution, or distance to major roads, deprivation index, hearing impairment, sensitivity to noise, or chronic diseases (which could affect noise perception and PA (Brownson et al., 2009)). We also explored daytime sleepiness as a potential mediator between noise annoyance and PA performance at SAP 3, by comparing the above-mentioned models with and without adjustment for it.

In interaction analyses, we evaluated different personal characteristics that might modify the longitudinal association, namely: age, sex, BMI, chronic disease, hearing impairment, day sleepiness, noise sensitivity (single item), size of parks/leisure areas, and study area by adjusting for a multiplicative interaction term between the categorical modifier and the 10-y transportation noise annoyance in addition to the adjustment for the categorical variable.

In sensitivity analyses to study the impact of exposure misclassification by residential mobility, we excluded movers from SAP 1 to 2 and from SAP 2 to 3.

We expressed associations with PA per 1-point increase in annoyance rating unless differently specified and defined statistical significance at an alpha level of 0.050, except for interactions where we considered an alpha level of 0.200. The term annoyance always referred to noise annoyance.

Analyses were done using Stata version 13.0 (StataCorp, College Station, TX, USA) and R version 3.1.3 (the R Foundation for Statistical Computing, Vienna, Austria).

3. Results

The main characteristics of the study sample are reported in Table 1 and in Appendix A, Table A.4. The median age of the study sample was 60 years [25th–75th percentiles): 50.6–67.8], 50.7% were women and 30.9% had a high educational level. A total of 57.1% were active in

Table 1
Characteristics of the study sample at SAP 3, in total and by groups of moderate physical activity at SAP 3 (inactive: <150 min/week; active: ≥150 min/week).

Variable	Inactive	Active	Total	p-Value[a]
Noise annoyance (NA)				
10-y mean transportation NA (SAP 1 + 2), ≥ 5; [*n* (%)]	489 (29.7)	606 (27.6)	1095 (28.5)	0.157
Change in transportation NA (SAP 3–2); [*p50* (*IQR*)][b]	0 (3)	0 (3)	0 (3)	0.284
1-y mean road traffic NA at night (SAP 3), ≥5; [*n* (%)]	132 (8.0)	155 (7.1)	287 (7.5)	0.266
1-y mean railway NA at night (SAP 3), ≥5; [*n* (%)]	17 (1.0)	27 (1.2)	44 (1.1)	0.568
1-y mean aircraft NA at night (SAP 3), ≥5; [*n* (%)]	52 (3.2)	64 (2.9)	116 (3.0)	0.665
1-y mean transportation NA (SAP 3), ≥5; [*n* (%)]	286 (17.4)	356 (16.2)	642 (16.7)	0.346
Physical activity (PA) at SAP 3				
Moderate PA, active[c]; [*n* (%)]	0	2195 (100)	2195 (53.1)	<0.001
Vigorous PA, active[d]; [*n* (%)]	254 (15.4)	661 (30.1)	915 (23.8)	<0.001
Total PA, active[e]; [*n* (%)]	602 (36.6)	2195 (100)	2797 (72.8)	<0.001
Covariates at SAP 3				
Age; [*p50* (*IQR*)]	57.6 (16.8)	62 (16.6)	60.2 (17.1)	<0.001
Sex, female; [*n* (%)]	866 (52.6)	1083 (49.3)	1949 (50.7)	0.047
Educational level, low; [*n* (%)]	93 (5.6)	79 (3.6)	172 (4.5)	0.007
Middle	1040 (63.1)	1442 (65.7)	2482 (64.6)	
High	514 (31.2)	674 (30.7)	1188 (30.9)	
Civil status, married; [*n* (%)]	1109 (67.3)	1520 (69.2)	2629 (68.4)	0.377
Divorced/living apart	209 (12.7)	250 (11.4)	459 (11.9)	
Widowed	102 (6.2)	147 (6.7)	249 (6.5)	
Single	227 (13.8)	278 (12.7)	505 (13.1)	
Second-hand smoking, yes; [*n* (%)]	244 (14.8)	215 (9.8)	459 (11.9)	<0.001
Smoking, never smokers; [*n* (%)]	839 (50.9)	1115 (50.8)	1954 (50.9)	0.001
Former smokers	505 (30.7)	764 (34.8)	1269 (33.0)	
Current	303 (18.4)	316 (14.4)	619 (16.1)	
Pack-years smoked in life (pack-year); [*p50* (*IQR*)]	0.1 (17.2)	0.4 (17.3)	0.2 (17.2)	0.754
Alcohol, daily; [*n* (%)]	411 (25.0)	585 (26.7)	996 (25.9)	0.023
Weekly	680 (41.3)	967 (44.1)	1647 (42.9)	
Rarely	389 (23.6)	465 (21.2)	854 (22.2)	
Abstinent	167 (10.1)	178 (8.1)	345 (9.0)	
Fish, ≥once/week; [*n* (%)]	1059 (64.3)	1493 (68.0)	2552 (66.4)	0.016
Cooked vegetables, ≥5 days/week; [*n* (%)]	904 (54.9)	1256 (57.2)	2160 (56.2)	0.149
Raw vegetables, ≥5 days/week; [*n* (%)]	1093 (66.4)	1634 (74.4)	2727 (71.0)	<0.001
BMI, <20; [*n* (%)]	88 (5.3)	115 (5.2)	203 (5.3)	<0.001
20–24.9	568 (34.5)	846 (38.5)	1414 (36.8)	
25–29.9	643 (39.0)	881 (40.1)	1524 (39.7)	
30–34.4	263 (16.0)	287 (13.1)	550 (14.3)	
≥35	85 (5.2)	66 (3.0)	151 (3.9)	
Menopause, pre-menopause; [*n* (%)]	165 (10.0)	155 (7.1)	320 (8.3)	<0.001
Peri-menopause	94 (5.7)	88 (4.0)	182 (4.7)	
Post-menopause	607 (36.9)	840 (38.3)	1447 (37.7)	
Men	781 (47.4)	1112 (50.7)	1893 (49.3)	
Hearing impairment, slight; [*n* (%)]	315 (19.1)	486 (22.1)	801 (20.8)	0.034
Severe	62 (3.8)	97 (4.4)	159 (4.1)	
None	1270 (77.1)	1612 (73.4)	2882 (75.0)	
Study area, Basel; [*n* (%)]	236 (14.3)	280 (12.8)	516 (13.4)	<0.001
Wald	353 (21.4)	348 (15.9)	701 (18.2)	
Davos	98 (6.0)	230 (10.5)	328 (8.5)	
Lugano	212 (12.9)	285 (13.0)	497 (12.9)	
Montana	153 (9.3)	282 (12.8)	435 (11.3)	
Payenne	257 (15.6)	181 (8.2)	438 (11.4)	
Aarau	205 (12.4)	390 (17.8)	595 (15.5)	
Geneva	133 (8.1)	199 (9.1)	332 (8.6)	
1-y mean road traffic noise levels, L_{24h} [dB(A)]; [*p50* (*IQR*)]	50.3 (11.1)	50.0 (10.8)	50.1 (10.9)	0.076
1-y mean PM_{10} levels (μg/m^3); [*p50* (*IQR*)]	18.9 (3.5)	19.2 (3.8)	19.1 (3.6)	0.303
Park/leisure area in a 2000 m radius buffer around residence (Hm^2); [*p50* (*IQR*)]	12.5 (51.0)	7.6 (49.5)	9.4 (51.0)	0.086
Distance from residence to major road (m); [*p50* (*IQR*)]	201.8 (542)	235.7 (609)	223.7 (576)	0.017
Mean Epworth sleepiness score; [*p50* (*IQR*)]	14 (5)	14 (5)	14 (5)	0.245
Noise sensitivity (0: low; 6: high); [*p50* (*IQR*)]	3 (4)	3 (4)	3 (4)	0.728

[a] Kruskal-Wallis test for continuous variables and X^2 test for categorical variables by groups of the outcome variable.
[b] p50: median. IQR: interquartile range.
[c] ≥150 min/week
[d] ≥120 min/week
[e] Active in moderate and/or vigorous or equivalent combined PA (moderate PA + 2*vigorous PA: ≥150 min/week).

moderate PA, while 23.8% were active in vigorous PA, and a 72.8% in total PA.

A total of 16.7%, 7.5%, 3%, and 1.1% participants at SAP 3 were at least moderately noise annoyed (score ≥ 5) by transportation, road, aircraft, and railway during the last year, respectively (Table 1). This prevalence was greater in the past, reaching 28.5% for the 10-y transportation noise annoyance (SAP 1 + 2). Indeed, the mean difference in annoyance rating between SAP 3 and 2 was −0.62 (standard deviation = 2.91).

Compared to physically inactive participants, active participants in moderate PA reported slightly less annoyance, particularly for 10-y transportation noise annoyance (Table 1). They were also on average 4 years younger, had generally healthier lifestyle, lived slightly closer to parks/leisure areas, and further away from major roads [medians

(IQR): of 235.7 m (608.8 m) vs. 201.8 (542)], but were exposed to similar L_{24h} or PM_{10} levels.

The Spearman rank correlation (r) between 1-y transportation noise annoyance at SAP 3, SAP 2 and SAP 1 was 0.42 (SAP 3-SAP 2), 0.29 (SAP 3-SAP 1) and 0.37 (SAP 2-SAP 1), (Appendix A, Table A.5). The 10-y transportation noise annoyance (SAP 1 + 2) was moderately correlated with the change in noise annoyance between SAP 2 and 3 ($r = -0.41$) and with 1-y transportation noise annoyance at SAP 3 ($r = 0.41$). It was also related to 1-y nighttime road traffic noise annoyance ($r = 0.32$) but not to railway ($r = 0.07$) or aircraft noise annoyance ($r = 0.05$) at SAP 3, not present in all areas. Correlations of noise annoyance with the environmental factors were highest with L_{24h} ($r = 0.4$) and lowest with parks/leisure areas ($r = 0.02$). The highest correlations with noise sensitivity were found for 10-y transportation noise annoyance (r between 0.04 and 0.27).

Main results are summarized in Figs. 2 and 3. The 10-y transportation noise annoyance (SAP 1 + 2) was negatively associated with being active in moderate PA at SAP 3 [odds ratio (OR) = 0.968, 95% confidence intervals (95% CI): 0.940; 0.998 per 1-annoyance point and the association was linear (Appendix A, Fig. A.1). Results remained similar (<1% change in estimated effects) with or without adjustment for changes in annoyance between SAP 2 and 3 (Appendix A, Table A.6). In contrast, changes in annoyance were not associated with PA, irrespective of adjusting or not for long-term annoyance.

Cross-sectional analyses at SAP 3 were consistent with longitudinal analyses (Fig. 3), particularly for 1-y nighttime road traffic and aircraft noise annoyance.

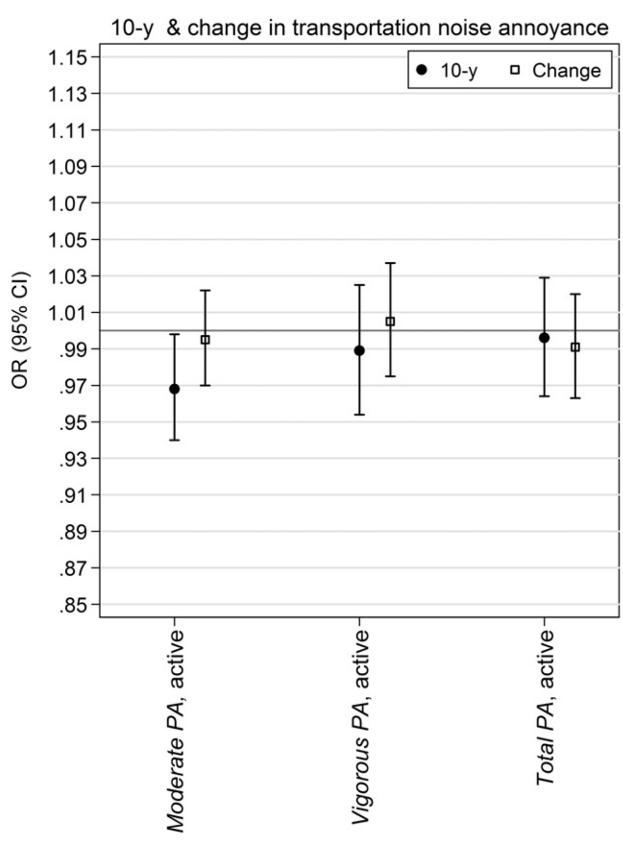

Fig. 2. Odds ratios (OR, dots) and 95% confidence intervals (95% CI, spikes) for the association of 10-y transportation noise annoyance (SAP 1 + 2) and its change (SAP 2 to 3) with being active in moderate (≥150 min/week), vigorous (≥120 min/week) and total PA (≥150 min/week) at SAP 3, per 1-annoyance rating point. Longitudinal logistic regression adjusted for age, sex, menopause, educational level, civil status, smoking, passive smoking, alcohol, diet, BMI, moderate PA at SAP 2, and including a random effect by study area. Models were mutually adjusted for the change in transportation noise annoyance from SAP 2 to 3 (squares) or 10-y transportation noise annoyance (SAP 1 + 2), (dots).

Effect estimates across all models were robust to adjustment for additional confounders and for daytime sleepiness as a potential mediator (e.g. Appendix A, Table A.3). When adjusting for environmental factors we observed a statistically significant association between living further away from traffic and being active in moderate PA (OR = 1.008, 95% CI: 1.000; 1.017 per 100 m) (Appendix A, Table A.7), which was independent of transportation noise annoyance. For the rest of environmental factors, we observed non-significant negative associations with moderate PA in single-exposure models, which were closer to the null after adjustment for 10-y transportation noise annoyance. E.g. for L_{24h}: OR = 0.973, 95% CI: 0.931; 1.016, per 5 dB (single-exposure model), OR = 0.986, 95% CI: 0.941; 1.033, per 5 dB (after adjustment for annoyance).

Regarding effect modification (Fig. 4), the negative association between the 10-y transportation noise annoyance (SAP 1 + 2) and moderate PA at SAP 3 was greater among women (OR = 0.947, 95% CI: 0.912; 0.983) than men (OR = 0.994, 95% CI: 0.954; 1.036, p-value of interaction = 0.060), in participants reporting daytime sleepiness above the median (OR = 0.942, 95% CI: 0.904; 0.981) than the rest (OR = 0.990, 95% CI: 0.954; 1.028, p-value of interaction = 0.053) and in participants with chronic disease (healthy: OR = 0.990, 95%CI: 0.950; 1.032, ill: OR = 0.952, 95% CI: 0.917; 0.988, p-value of interaction = 0.124).

Finally, associations between 10-y transportation annoyance (SAP 1 + 2) and the PA outcomes at SAP 3 remained after excluding movers from SAP 2 to 3 (31.9%) and SAP 1 to 2 (50.3%) (Appendix A, Table A.8).

4. Discussion

To our knowledge, this is the first study to explore the impact of transportation noise annoyance on PA, a behavioral pathway through which noise may in part affect cardiometabolic diseases (Basner et al., 2011; Dzhambov, 2015; Eriksson et al., 2014; Oftedal et al., 2015; Pyko et al., 2015), in addition to the direct (physiological) stress pathway. In this population-based cohort of adults, reported long-term transportation noise annoyance (mostly related to road traffic) at home was associated with being less active in moderate PA after controlling for a comprehensive set of potential confounders, including other environmental factors. Consistent relationships were observed also for yearly nighttime road traffic and aircraft noise annoyance at SAP 3 in cross-sectional analyses. Associations between the 10-y transportation noise annoyance and moderate PA seemed to be stronger for women, those reporting day sleepiness, and those with chronic diseases. We also observed a negative association between residential proximity to major roads and moderate PA, but not for residential outdoor levels of road traffic noise and PM_{10}, and size of parks/leisure areas around home, particularly after adjustment for noise annoyance.

Noise annoyance may be a relevant environmental factor in the context of a global environmental quality perception that impacts PA (Brownson et al., 2009; Saelens et al., 2003). Our results may be in line with soundscape studies, which indicate that environments rated by individuals as having acoustic quality, are more attractive and promote healthy habits (Tjeerd and Andringa, 2013; van Kempen et al., 2014). Results may also agree with a few cross-sectional surveys on built environment that observed associations between traffic perception, a main source of noise and air pollution, and reduced PA (Brownson et al., 2009; Duncan et al., 2005; McCormack and Shiell, 2011).

While the magnitude of the estimated effects was small, noise annoyance still affects millions of people, thus it could substantially contribute to the burden of disease (World Health Organization and European Commission, 2011) related to physical inactivity, which is in turn a major risk factor for cardiometabolic diseases (Lee et al., 2012), mortality, and disability-adjusted life years (DALY's) worldwide (Institute for Health Metrics and Evaluation, 2013). Moreover, the studied associations were linear (Appendix A, Fig. A.1), suggesting that even low levels of noise annoyance could impact PA.

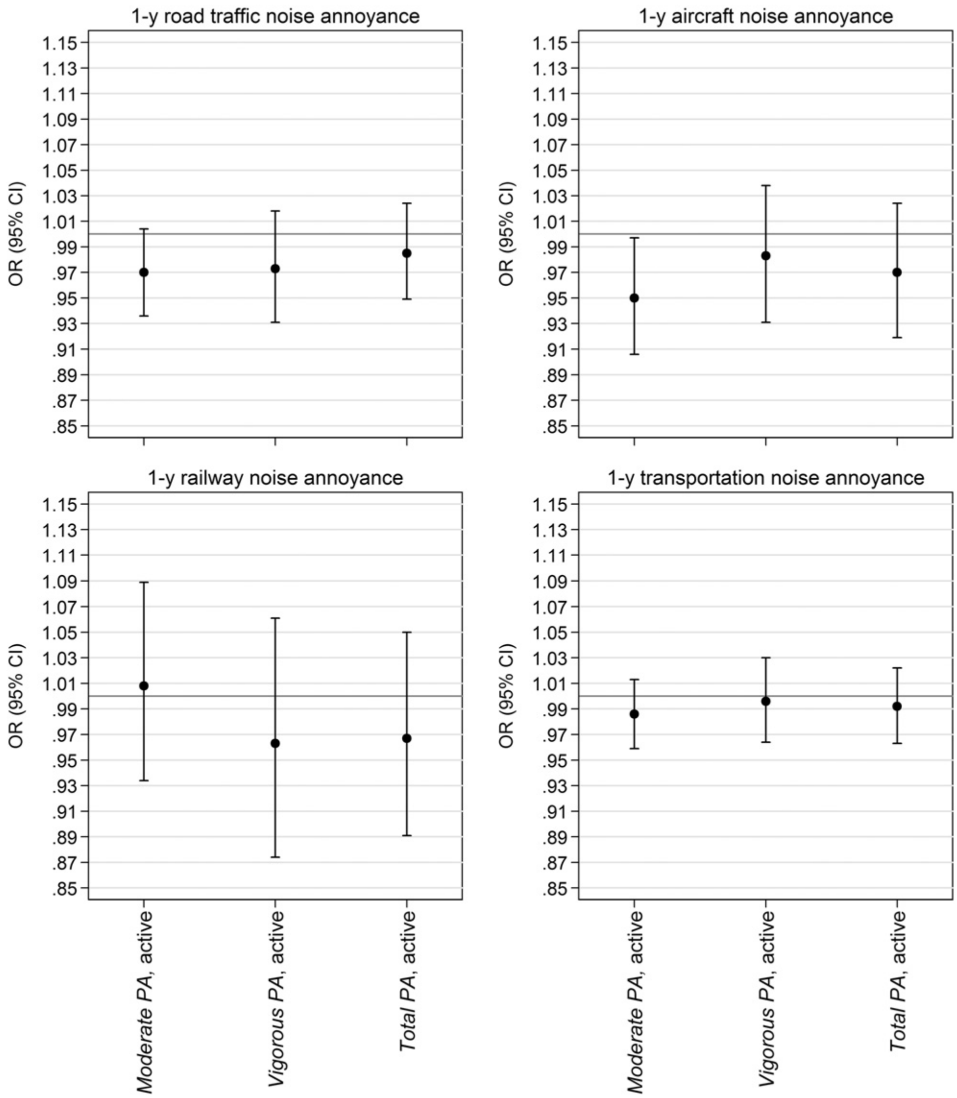

Fig. 3. Odds ratios (OR, dots) and 95% confidence intervals (95% CI, spikes) for the association of 1-y road traffic, railway, and aircraft noise annoyance at night, and 1-y transportation noise annoyance with being active in moderate (≥150 min/week), vigorous (≥120 min/week) and total PA (≥150 min/week), per 1-annoyance rating point. Cross-sectional logistic regression at SAP 3 adjusted for age, sex, menopause, educational level, civil status, smoking, passive smoking, alcohol, diet, BMI, and including a random effect by study area.

4.1. Physical activity and intensities

In this study, long-term transportation noise annoyance was mainly associated with moderate PA. These results could reflect different behaviors leading to moderate and vigorous PA performance. Vigorous PA relates to a greater exercise engagement and team sports, which might be performed far from home, whereas performing moderate PA could relate to specific activities, such as walking, which would be more dependent on the immediate environmental perception. This would agree with the associations observed between traffic perception and walking in previous literature (McCormack and Shiell, 2011).

Null findings with vigorous PA could be also partly due to the categorical nature of this PA question, for which a fine cut-off at 75 min/week was not possible. In turn, only by increasing its specificity, i.e. a cut-off at ≥120 min/week to identify true active cases, we could best differentiate intensities.

4.2. Types of noise annoyance

The combination of the 10-y transportation noise annoyance (SAP 1 + 2) with the changes (SAP 3–2), allowed us to explore a longer-term time window beyond the 1-y means at SAP 3 while accounting for variations in noise annoyance. Reductions in PA were associated with long-term noise annoyance, but not with its changes. To further understand the impact of the latter, we categorized participants between visits as being never/always/decreasingly or increasingly at least moderately annoyed (score ≥ 5). Interestingly, associations with moderate PA in multivariate models were only observed for participants always annoyed (reference: never annoyed): OR (95% CI) = 0.837 (0.682, 1.026, p-value = 0.088) for SAP 2–1, and OR (95% CI) = 0.793 (0.626, 1.003, p-value = 0.053) for SAP 3–2 (ancillary analysis, data not shown), although they were not statistically significant, probably due to reduced statistical power. This might suggest the potential of persistent long-term noise annoyance to chronically affect PA (and by this pathway contribute to cardiometabolic diseases).

The cross-sectional analyses also indicated the relevance of time windows of one year. They further allowed us to distinguish source-specific noise annoyance and explore associations at nighttime (in the bedroom), which is a susceptible period for noise effects due to restoration (Münzel et al., 2014). The most relevant sources seemed to be road traffic and aircraft, for which the literature on cardiometabolic endpoints is also vast (Babisch et al., 2013; Dzhambov, 2015; Eriksson et al., 2014; Ndrepepa and Twardella, 2011; Oftedal et al., 2015; Pyko

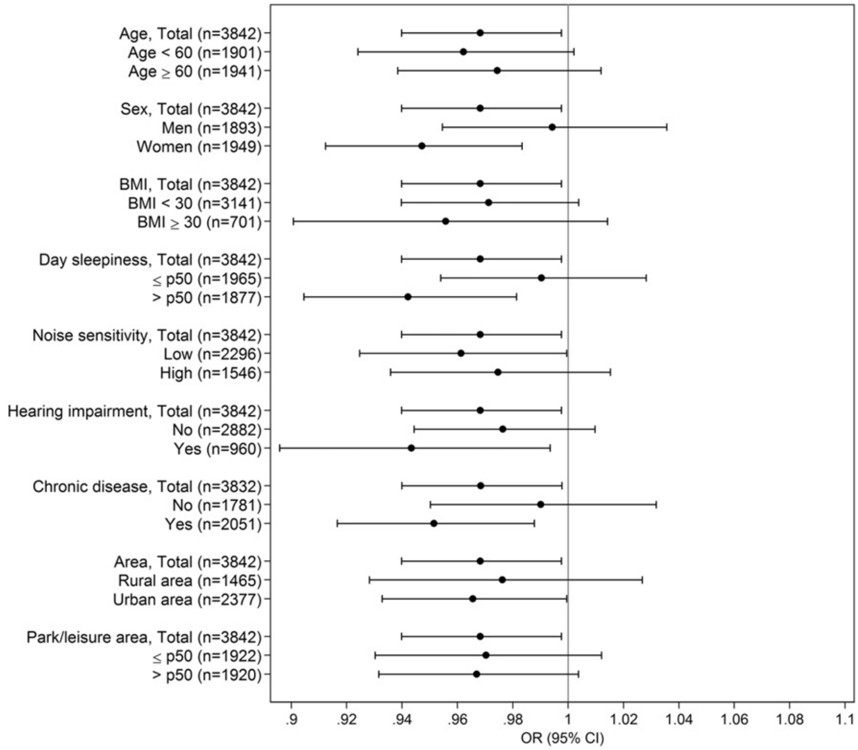

Fig. 4. Odds ratios and 95% confidence intervals for the association between 10-y transportation noise annoyance (SAP 1 + 2) and being active in moderate PA (reference: non-active) at SAP 3 by groups of participants' characteristics at SAP 3, per 1-annoyance rating point. Interactions tested with multiplicative interaction terms between annoyance and the studied characteristics. Logistic regression adjusted for age, sex, menopause, change in transportation noise annoyance (SAP 2 to 3), educational level, civil status, smoking, passive smoking, alcohol, diet, BMI, moderate physical activity at SAP 2, and including a random effect by study area. p-Values of interaction were >0.200 except for sex (p-value = 0.06), day sleepiness at SAP 3 (p-value = 0.053) and chronic disease (p-value = 0.124).

et al., 2015; van Kempen and Babisch, 2012; Vienneau et al., 2015). The null association for railway noise annoyance may be potentially due to the low levels of annoyance and railway noise exposure in this sample and was also in agreement with the little health-related evidence on the source (Dratva et al., 2012). Results also suggest a greater impact for the nighttime compared to 1-y transportation noise annoyance over the 24 h, as previously observed between nighttime noise levels and cardiovascular diseases (Basner et al., 2014); however, daytime effects cannot be discarded. Daytime effects may be more difficult to detect in our study, among others, because of the lower precision of the general transportation annoyance question, which did not identify the noise source, and its lower prevalence at SAP 3.

Finally, outdoor noise annoyance due to commercial activities and neighbors did not affect the studied associations (i.e. changes in the effect estimates for the main model < 1%, data not shown).

4.3. Effect modification

The negative association between 10-y transportation noise annoyance (SAP 1 + 2) and moderate PA at SAP 3 was stronger in women. Two previous studies reported stronger associations between transportation noise annoyance and quality of life for women, one specifically at SAPALDIA 2, and suggested that women rated their well-being worse (Dratva et al., 2010) or that noise perception was more relevant for women (Röösli et al., 2014). Assuming a daytime effect, this finding could also relate to a lower exposure misclassification in women, who may stay at home longer (working status, which relates to being outside home, was lower in women than in men: 63.5% vs. 52.2%, respectively, p-value of chi^2-test < 0.001).

We hypothesize that the stronger associations observed when reporting daytime sleepiness above the median and for participants with chronic diseases may relate to behavior. I.e. individuals with a feeling of impairment may be more susceptible to annoyance and/or encounter a greater barrier to exercise during the day. Although the studied association was not mediated by day sleepiness, the interaction with day sleepiness could also indicate that night-time noise leads to noise annoyance, sleep disturbance, subsequent sleepiness the day after, and low PA performance. While this could be an acute reaction, repeated noise annoyance could trigger chronic sleep disruption and reduced PA in the long-term. Refined indicators reflecting different sleep problems at night might be needed to study this further.

4.4. Mechanisms

In line with our main hypothesis results indicated a contribution of the indirect noise-related stress pathway (i.e. of noise annoyance) on PA, with no evidence for an influence of the objectively modeled road traffic noise levels, which may suggest the particular importance of the emotional/psychological reaction. Furthermore, we did not observe confounding by air pollution, proximity to major roads (a marker of near-road noise and air pollution levels and possible barrier for PA) or by parks/leisure areas (size of urban green areas, sports and leisure facilities around the home which could promote exercise and correlate with lower levels of road traffic noise and air pollution). Proximity to major roads was also associated with lower PA and not explained by noise annoyance or clearly confounded by the other environmental factors, although it was only marginally statistically significant after adjustment for PM_{10} (p-value = 0.066), or parks/leisure areas (p-value = 0.057) (ancillary analysis, data not shown). This might suggest its role as a barrier for PA or marker of environmental quality, independently of noise annoyance.

The greater contribution of noise annoyance goes in line with the few epidemiological studies on health-related quality of life, which observed decreases both in the mental and physical scores related most often to annoyance (Dratva et al., 2010; Héritier et al., 2014; Shepherd et al., 2010), whereas associations with noise levels were weak

(Héritier et al., 2014; Roswall et al., 2015) and potentially mediated through annoyance and sleep disturbance (Héritier et al., 2014). It may also reinforce previous observations about the fact that an environment that promotes healthy habits is more related to the appraisal of noise, than to its level (Tjeerd and Andringa, 2013; van Kempen et al., 2014).

Finally, while nighttime noise annoyance seemed to contribute and we also observed an interaction with day sleepiness, associations were not mediated by self-reported sleep problems. This might suggest that part of the noise annoyance mechanism may act through a direct decrease in the willingness to exercise during the day.

4.5. Strengths and limitations

A main strength of the present study was the use of a prospective population-based cohort with rich data. The longitudinal design allowed us to reduce reverse causality by analyzing annoyance previous to the outcome. We were also able to compare the independent relationships of long-term noise annoyance versus changes in annoyance. However, this first cohort finding should be further replicated and repeated measures with three time points should be performed to fully assess causality. The consistency between longitudinal and cross-sectional results additionally helped us to consider comprehensive information at SAP 3 which, to our knowledge, is rarely available altogether (Basner et al., 2014; Brownson et al., 2009). This included the evaluation of source-specific noise annoyance and relevant confounders, among others, objectively-assessed environmental factors.

As in most population-wide studies, a main limitation was the assessment of PA based on short questions (Wanner et al., 2013). While long questionnaires provide more detail, short questionnaires are needed due to space constraints. They are also advantageous in older populations, since they are less demanding and can be better answered (Wanner et al., 2013), thus they are also more suitable in prospective studies such as SAPALDIA. Also, despite the comprehensive adjustments available in this study, we cannot discard residual confounding by correlated environmental quality indicators associated with noise annoyance and PA, such as walkability. Nevertheless, walkability in Europe and especially in Switzerland is generally high, thus less associated with areas with little traffic (Ravalet et al., 2014; Reyer et al., 2014). Furthermore, results were not modified when stratifying by rural/urban areas, which could represent different quality environments and types of green areas. As another limitation, we assessed general transportation noise annoyance with old wording used at SAP 1 (year 1991). Nevertheless, it was assessed with the same ICBEN-type 11-item scale (Fields et al., 2001) as nighttime annoyance at SAP 3, and the consistency in results across types of annoyance suggests limited bias due to wording. Residential mobility was not a source of exposure misclassification and change in annoyance perception, given the robustness in findings when restricting the sample to non-movers. Response bias related to higher noise annoyance rating among those with diseases (Brownson et al., 2009; Roswall et al., 2015) seems unlikely. First, participants were not aware of our hypothesis and questions were separated in the questionnaire, and second adjusting for chronic diseases and depression did not change the estimated effects. Finally, although we could not adjust for deprivation index and the noise sensitivity score (instead of the noise sensitivity single item) in the main model, no differences in estimated effects were revealed when adjusting for them in the available samples (Appendix, Table A.8).

5. Conclusions

In conclusion, long-term transportation noise annoyance was associated with reduced PA at follow-up and the impact was also related to road traffic and aircraft noise annoyance at night. This risk could be particularly relevant for individuals with sleep problems, chronic disease and among women. This study adds to the evidence on potential mechanisms of noise towards chronic diseases. In addition to the direct stress pathway, which may be the most relevant during sleep for cardiovascular disease (Münzel et al., 2014), the indirect pathway through persistent noise annoyance and lower PA, could be also important, particularly in emerging noise-related adverse health effects such as obesity and diabetes (Dzhambov, 2015; Eriksson et al., 2014; Oftedal et al., 2015; Pyko et al., 2015). These findings are of public health relevance, because of the importance of PA for health and the prevalence of noise annoyance. Further studies are needed to confirm these novel results and to inform about the most affected types and areas of PA with additional environmental quality data. Whether the noise annoyance mechanism acts through sleep impairment and/or through the direct perception of a less attractive environment will also require further verification.

Conflict of interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.envint.2016.03.011.

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