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Lowering urban speed limits to 30 km/h reduces noise annoyance and shifts exposure–response relationships: Evidence from a field study in Zurich

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A R T I C L E I N F O

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A B S T R A C T

Background: The city of Zurich progressively pursuits a strategy of reducing road traffic noise by lowering the speed limit to 30 km/h on street sections that exceed the legal noise limits.
Aim of this study was to evaluate the effects of the reduced speed limit on noise levels (Lday and Lnight), noise annoyance, self-reported sleep disturbance, perceived road safety, and in particular, to elucidate if the reduced speed limit leads to a shift of exposure–response relationships towards lower effects.
Methods: We surveyed about 1300 randomly sampled inhabitants, in a repeated measures study, before and after the speed rule changeover from 50 km/h to 30 km/h along 15 city street sections, by postal questionnaire. Concurrently, individual noise exposure calculations based on traffic counts and on-site speed measurements were carried out before and after the changeover.
Results: Road traffic noise Leq's at the loudest façade point dropped by an average of 1.6 dB during day and 1.7 dB at night. A statistically significant decrease of noise annoyance and of self-reported sleep disturbances was observed, as well as a moderate but significant increase of perceived road safety. Most importantly, the exposure–response relationships for annoyance and sleep disturbance were shifted towards lower effects in the 30 km/h condition by, depending on receiver point, between about 2 dB and 4 dB during the day and about 4 dB at night, indicating lower effects at the same average level. This is a hint that, in addition to lower average exposure levels alone, other factors related to the lower driving speed additionally reduce noise annoyance and sleep disturbance.
Conclusions: City dwellers probably benefit from traffic speed reductions to a greater degree than would be expected from the reduction in average level attained by the lower driving speed alone.

1. Introduction

From a public health perspective, road traffic is one of the most important causes of injuries and non-communicable diseases – including those caused by air pollution and noise (Nieuwenhuijsen and Khreis 2020). The adverse health effects of road traffic noise are greatest in urban areas, where traffic densities and exposure levels are high. Lowering speed limits is a cost-effective and efficient noise abatement measure as there is a measurable link between traffic noise and speed: E.g. at higher speeds above 60 km/h, it can be seen that a difference in speed of 10 km/h leads to an increase in noise level of more than 1 dB for each passing passenger car, and about 1.7 dB for a truck (Deok-Soon and Byung-Sik 2016). The Leq reduction potential of a 30 km/h speed limit replacing a 50 km/h speed limit has been reported to be – at best – up to 5 dB, depending on street design, share of heavy vehicles and compliance of drivers with the new speed regime (Bühlmann and Egger 2017; Heutschi 2015). If the well-established dose–response principle is taken as a basis, lower noise levels following a speed reduction are naturally expected to result in lower annoyance (and of course other noise related health outcomes). In the domain of road traffic noise, intervention measures to reduce exposure usually lead to a reduction of annoyance whereas this reduction can be expected to be at least the magnitude estimated by a steady state exposure–response relationship (Brown and van Kamp 2017). When a noise situation is abruptly changed, annoyance of residents usually changes in a way that cannot easily be predicted by previously derived exposure–response relationships, as such abrupt changes often trigger excess responses (Brown and van Kamp 2009a), also called “overreaction” or “overshoot” responses (Guski 2003). Such

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excess responses can persist for several years. This has to be kept in mind whenever one investigates reactions to changes in the noise environment.

The WHO reported in their Environmental Noise Guidelines that there is room for improvement regarding the quality of the evidence on the effectiveness of interventions to reduce exposure to and health outcomes from environmental noise (WHO 2018). In fact, field studies that investigate the effect of speed reductions on changes in noise annoyance are scarce: The most comprehensive review on the effect of interventions to reduce noise at source to date includes a range of intervention studies, but none in which the intervention consisted of a reduction of the speed limit (Brown and van Kamp 2017). In the present study we thus aim to elucidate effects of speed reductions not only on exposure levels, but particularly on self-reported health effects such as annoyance and noise-induced sleep disturbance. The case we investigate is the city of Zurich (pop. 430′000) where legal exposure limits for road traffic noise are exceeded on a network of about 230 km length.

To bring down noise levels, the city authorities in Zurich have in the last few years introduced a 30 km/h speed limit on almost 40 km of the street network. For the purpose of evaluating the effectiveness of this measure, we carried out an empirical longitudinal survey and corresponding individual exposure calculations among residents where the change from speed limit 50 km/h to speed limit 30 km/h took place in the form of a “before-after” comparison. The study’s goals were to investigate whether and to what extent the speed reduction led to a reduction in average noise exposure, noise annoyance and self-reported sleep disturbance due to noise, as well as to an increase in the perceived road safety in the respective street. In addition, it was investigated if and to which degree exposure–response relationships differ between the 50 km/h and 30 km/h speed limit and if they are shifted towards lower effects. Such shifts have conceptually been described long ago, e.g. by Kastka (1981). We also investigated if there are relevant effect modifiers that impact on the effect of speed reduction on annoyance and sleep disturbance and on exposure–response relationships of these effects.

2. Methods

2.1. *Study design and sampling procedure*

In noise effects research terminology, this study was of the type “intervention study”, with subtype “source intervention”, according to the classification used by the WHO (Brown and van Kamp 2017; WHO 2018). The study was carried out between 2017 and 2020 among randomly contacted residents on 15 small and mid-sized street sections (of a total length of 6 km) in the city of Zurich that in this period were affected by the changeover from the 50 km/h to the 30 km/h speed limit. Within the defined survey perimeters, resident addresses for each building were obtained from the official register by the Population Office of Zurich, linked to the federal building and dwelling identifier variable (EGID/EWID) that allows a unique assignment of persons to a building or dwelling unit. The sampling was restricted to buildings with Lnight above 40 dB at the loudest façade point. Subsequently, the original address pool was reduced to one person per dwelling unit by random assignment, yielding a gross sample of N = 3732 individuals. These randomly determined persons were then contacted by post *before* the changeover (fill-out date of questionnaire on average 95 days before) and asked to complete a questionnaire on their perception of road traffic noise in their street. Respondents were in a followup survey contacted again *after* the changeover (fill-out date of questionnaire on average 393 days after the changeover) and asked to complete another questionnaire (with largely the same items/questions). The participants were asked about the noise annoyance they experienced and about their sleep disturbances and perceived road safety in relation to a retrospective period of 6 months before the questionnaires were completed (and as opposed to the usual 12-month period according to the ICBEN recommendation (Fields et al. 2001)). This procedure allowed for a pairwise before-and-after comparison of responses, in other words, a repeated measures statistical design (Fig. 1). Data protection authorities and the ethics committee of the Canton of Zurich have examined this procedure and approved it.

Because seasonal effects potentially moderating noise annoyance (e.g. due to temperature-dependent window closing behavior) could not be ruled out, it was originally planned to conduct both before and after-surveys at the same time of the year. However, for some street sections, this strict planning proved impossible to implement in practice. This was partly due to (technical) delays in the resignaling and partly due to the COVID-19 pandemic, which had led to an unforeseeable drop in traffic figures in the months March to June 2020. Because of the latter, for some street sections the after-surveys had to be postponed to obtain comparable traffic conditions during both the before and after condition. As far as possible, the cover letters and questionnaires were sent out on the same date as the before-survey one year earlier, or, for the above stated reasons, later, but not earlier. The participants should have ample time to get used to the new lower speed regime at their street. For the after-survey, only persons who had returned the questionnaire of the previous survey (N = 1311) were contacted again.

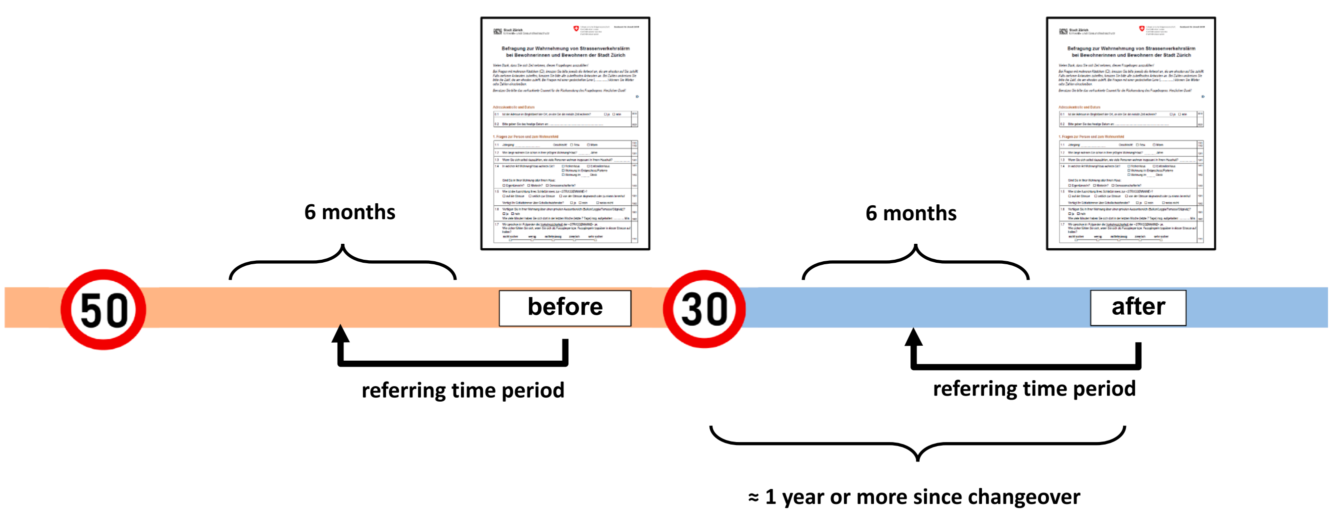

Fig. 1. Study design with “before”-survey during the previous 50 km/h regime (orange bar) and “after”-survey with the same persons after the changeover to 30 km/h (blue bar) (in the after-survey, only those persons were contacted who had participated in the before-survey). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

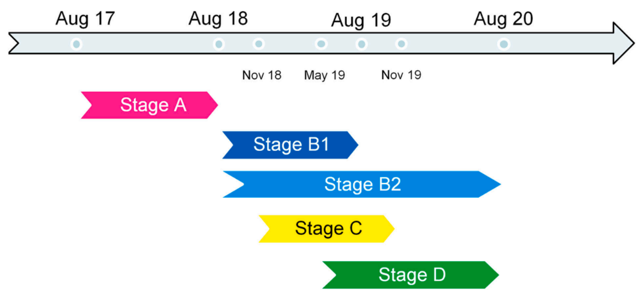

Fig. 2. Survey stages within the entire study duration. Arrow beginnings stand for the (first) mail dispatch of the before-survey, arrow ends for the (last) dispatch of the after-survey in each stage.

The whole study covering 15 street sections took place in a total of five "stages" (A, B1, B2, C, D). Each stage comprised (1) before-survey mailout at the specified street sections, (2) speed rule change to the new 30 km/h speed regime, and (3) mailout of after-survey questionnaire. The stages followed the schedule of the installment of the traffic signs and other work carried out for the new speed rule by the public works department of the city. The changeovers included new traffic signs, in some cases new pavement markings, and in a few cases, the installation of plastic speed bumps. No other road construction measures were realized. The after-survey took place on average 478 days after the before-survey. Fig. 2 shows pertinent time periods and stages.

2.2. Questionnaire

A four-page paper and pencil questionnaire was used. The questionnaire was entitled "Survey on the perception of road traffic noise among residents of the city of Zurich" and was sent out together with a cover letter by the City of Zurich, i.e. as official mailing, with the city seal in the header. Responses were collected by means of a prepaid reply envelope and transformed into a digital format. Both a before and an after version of the questionnaire was created, which were identical apart from a few exceptions. The questionnaire started with some general questions (age, sex, family and housing circumstances, length of residence, household size, housing type, house/apartment ownership, bedroom location relative to nearest street (facing street, sideways, or away from street) followed by questions about annoyance from different noise sources, about noise-induced sleep disturbance, and perceived road safety. The degree of annoyance was measured using both the numerical 11-point and verbal 5–point ICBEN scale with the scale values "not at all", "slightly", "moderately", "very", "extremely" (Fields et al. 2001). Respondents with answers on one of the top two scale points ("very" or "extremely", corresponding to 40 % of the scale length as proposed by Fields et al. (2001)) were defined as "highly annoyed". The degree of noise-induced sleep disturbance was measured using an 11-point scale. Respondents with scale values ≥ 8 were defined "highly sleep disturbed".

2.3. Noise exposure assessment

Two data sources were available to determine the noise emissions on the street sections before and after the changeover: On the one hand the noise pollution cadaster of the Environmental and Health Protection Department and on the other hand the traffic reports of the Transport Department of the City. These include data about traffic volumes for different vehicle categories as well as the frequency distribution of driven speeds and are regularly carried out to evaluate the success of speed reduction measures. The emission calculations were performed using the Swiss emission calculation model sonROAD18 (Heutschi and Locher 2018) (without directional correction). In order to simplify the process, the emission calculations in the 50 and the 30 km/h regime were based on the same traffic volumes, basically those of the traffic reports for the 50 km/h regime. This simplification is justifiable, since, according to a report from the Transport Department, traffic volumes on the whole street network remain very stable over the years (Stadt Zürich Dienstabteilung Verkehr, 2022). In addition, evasive traffic on other routes as a result of the introduction of the 30 km/h speed limit could practically be excluded because taking another route instead of the most direct one would in most cases not reduce driving time from A to B in the city.

The exposures on the building façades and at the presumed bedroom window (identified for each case individually with the help of Google Streetview) were calculated with the software CadnaA, based on the digital terrain model of the official cadastral survey (DTM-AV) and the 3D city model of the city of Zurich. We determined the exposure at the faintest (min), loudest (max), and at the bedroom façade for each individual dwelling unit, both in the before and after condition, for the daytime (Lday, i.e. the Leq between 06 and 22 hrs) and nighttime (Lnight, i.e. the Leq between 22 and 06 hrs) period. The analyses in this article were made for the outcomes annoyance and perceived road safety as a function of LDay at the loudest façade point, and for the outcome sleep disturbance as a function of LNight at the bedroom façade.

2.4. Statistical analysis

The (anonymized) answers in the questionnaires were first checked for plausibility. Questionnaire data were linked with the noise exposure data. The final dataset contained two records per person, one for the before and one for the after condition, with complete exposure values as well. All statistical analyses were carried out in R version 3.5.1 (R Core Team 2018) using the packages 'base', 'lme4′, 'DescTools' and 'ggplot2′. For all statistical analyses, the significance level was set at a value of 5 % ($p < 0.05$).

3. Results

3.1. Response statistics

A total of 3732 questionnaires were sent out in the before-survey. Of these, 1311 were returned, resulting in an initial response rate of 35 %. Since for the after-survey only persons were contacted who had returned the questionnaire of the previous survey, 1311 questionnaires were sent out for the after-survey. Of these, 886 were returned, thereof 880 with a validated address. In the end, we had paired data for 880 individuals (this corresponds to 24 % of the original mailing), i.e. 1760 data records for statistical analysis of before-after changes. This sample comprised of 480 female (55 %) and 394 (45 %) male participants. The mean age was 53 years.

3.2. Driving speeds and noise exposure before and after the changeover

Table 1 shows mean values and standard deviations of the measured speeds during the before and after-survey (averaged over all street sections and related subsections; total $N = 48$). As can be seen, the new speed limit was well respected on average. An initial overview of the average noise exposure at the loudest and quietest façade point and at the bedroom façade before and after the changeover, and its change, is presented in Table 2.

The density distributions of the calculated exposure levels during the day and at night are shown in Fig. 3 both for the before and after condition. The mean achieved reductions of the exposure amounted to 1.58 dB during day (loudest façade) and 1.33 dB during night (bedroom façade). The average level reduction of slightly<2 dB corresponds with the average speed reduction of just under 10 km/h, which is quite in line with expectations.

Table 1
Mean values and standard deviations of the average speed ($V_{average}$) during the day and night in the 50 km/h and the 30 km/h speed regime, and their differences [in km/h].

	50 km/h day	30 km/h day	Difference day	50 km/h night	30 km/h night	Difference night
Mean value	39.88	30.97	8.91	41.23	31.51	9.72
Standard dev.	1.99	2.69	2.78	1.90	2.70	2.26

Table 2
Means and standard deviations (in parentheses) of road traffic noise levels (LDay and LNight) before and after the changeover, and their differences [in dB].

	50 km/h LDay	30 km/h LDay	Difference LDay	50 km/h LNight	30 km/h LNight	Difference LNight
Loudest (max.)	57.81	56.24	−1.58	51.11	49.42	−1.71
Façade point	(4.44)	(4.46)	(0.53)	(4.38)	(4.3)	(0.49)
Quietest (min.)	40.84	40.18	−0.67	34.39	33.73	−0.68
Façade point	(3.25)	(3.22)	(0.41)	(3.53)	(3.55)	(0.4)
Bedroom	51.11	49.9	−1.25	44.5	43.2	−1.33
	(7.48)	(7.12)	(0.67)	(7.45)	(7.05)	(0.66)

3.3. Scores for annoyance, self-reported sleep disturbance, HA and HSD, and self-assessed road safety in the before (50 km/h) and after (30 km/h) condition

The following analyses show before-after comparisons of annoyance, self-reported sleep disturbance, and self-assessed road safety at residence.

Annoyance and sleep disturbance. Fig. 4 shows mirrored histograms of the frequency of selected response categories for the variables annoyance and noise-induced sleep disturbance in the before (50 km/h) and after (30 km/h) condition. It becomes apparent that higher annoyance score values occur only about half as often during the 30 km/h speed regime as during the 50 km/h speed regime. A similar effect can be observed with sleep disturbance (Fig. 4, bottom).

Fig. 5 shows the distributions of annoyance and sleep disturbance ratings, both on the 11-point scale, in the before and after-surveys as violin plots with mean. Mean differences between the speed regimes were examined using two-tailed t-tests for dependent samples and were both significant (Annoyance: $\Delta = 0.63$ points on the 11-point scale, $t = 7.84$, $df = 851$, $p < 0.01$; Sleep disturbance: $\Delta = 0.55$ points on the 11-point scale, $t = 6.35$, $df = 854$, $p < 0.01$).

Fig. 6 shows the share of highly annoyed persons (%HA, top) and highly sleep disturbed (%HSD, bottom) in discrete LDay and LNight level categories. It becomes clear that in absolute terms, the largest decreases in %HA are to be found among more severely annoyed persons, i.e. rather in the upper level categories. Again, a similar observation can be made for the outcome %HSD.

Road safety. Respondents were asked in the before and after-survey about their subjectively perceived road safety in the street affected by the new speed limit. The response scale included five levels (“not safe”, “not much safe”, “moderately safe”, “rather safe”, “very safe”). A corresponding mirrored histogram is shown in Fig. 7. In order to determine whether the average subjective perception of road safety increased in a statistically significant manner after the changeover to 30 km/h, the original verbal scale was transformed into a 1–5 interval scale (for the sake of simplicity, the five verbal scale values were assumed to be equally spaced) and the difference in means was tested using a *t*-test. The result shows a slight increase in the perception of road safety at 30 km/h

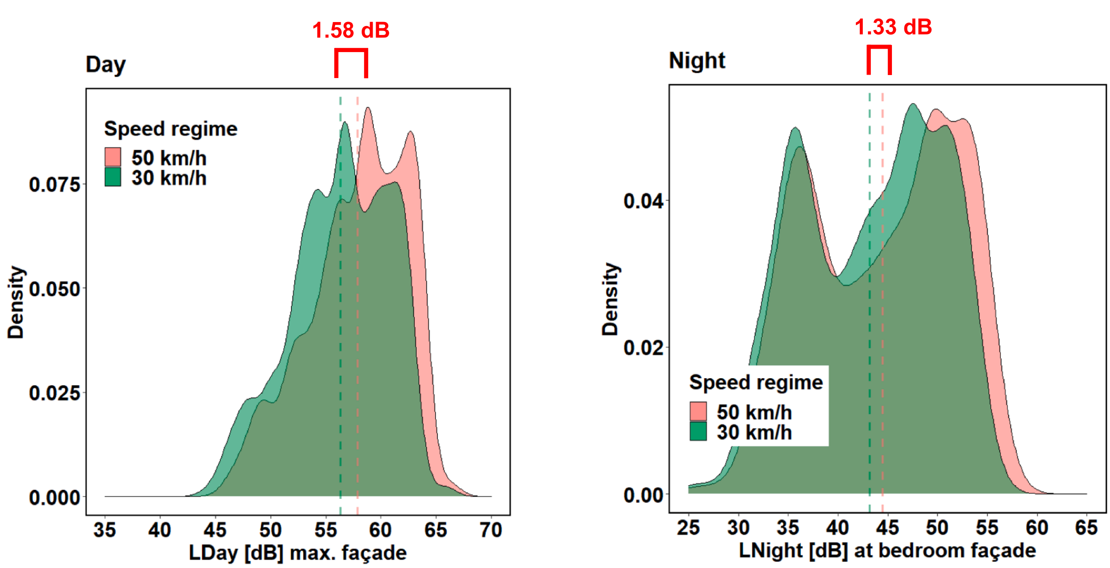

Fig. 3. Estimated density distributions of the average road traffic noise level during the day (left) and at night (right) for the two different speed regimes. The dashed vertical lines indicate the respective mean value. Distributions created with a Kernel density estimation with Gaussian kernel.

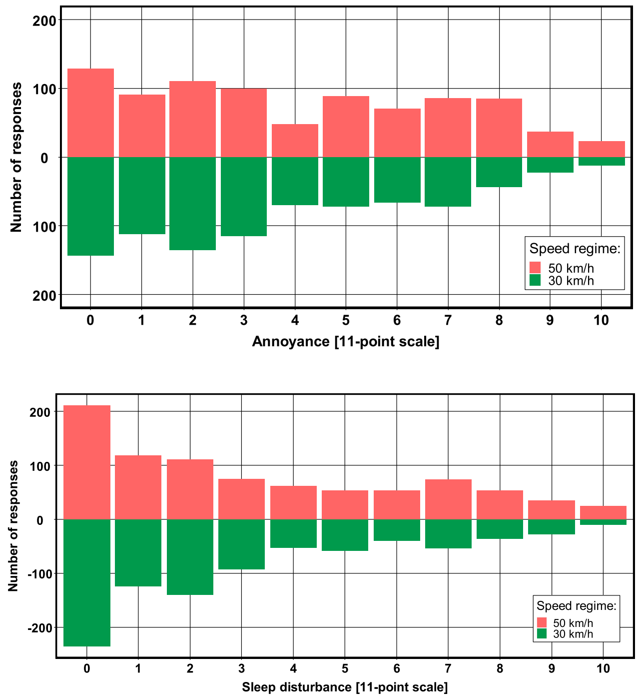

Fig. 4. Mirrored histograms showing the distribution of annoyance responses on the 11-point ICBEN scale (top) and of noise-induced sleep disturbance responses on a similar 11-point scale (bottom), during the before (50 km/h, red) and the after-survey (30 km/h, green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

compared to 50 km/h, with the difference in mean proving to be significant (two-tailed *t*-test for dependent samples: $\Delta = 0.25$ points, $t = 7.714$, $df = 851$, $p < 0.01$).

3.4. Exposure-effect relationships for %HA and %HSD in the 50 km/h and 30 km/h condition

The analyses presented so far pointed out the observed changes in the mean and the distribution of some key outcome variables. They indicate a decrease in annoyance and self-reported sleep disturbance, and a slight but significant increase in perceived road safety after switching from the 50 km/h to the 30 km/h speed regime. However, these analyses do not show whether and to what extent the exposure–response *relationships* for annoyance and self-reported sleep disturbance changed or shifted after the changeover. Thus, the question is whether the observed reduction in annoyance and sleep disturbance is adequately explained by the reduction in the average exposure alone. It is quite possible that, in addition to the reduction of the average exposure level, factors such as less rapidly rising pass-by levels or lower maximum levels additionally reduce annoyance and/or sleep disturbance – to momentarily leave aside so called *change effects* that provide alternative explanations (Brown and van Kamp 2009b). In this case, the entire exposure–response curves would have to shift towards lower effects under the 30 km/h regime. To test this, we calculated corresponding statistical models and plotted the respective exposure–response curves for %HA and %HSD for the before condition (50 km/h) and the after condition (30 km/h), respectively, side by side in Fig. 8. To do so, multilevel logistic regression models were computed, with the speed regime condition (i.e., whether the questionnaire was completed before or after the change to 30 km/h) defined as a fixed and the respondent as a random intercept effect. This approach takes into account that responses in both the 50 km/h and 30 km/h condition are clustered within the same individual. Parameter estimates of these models are given in Table 3.

Fig. 8 above shows that for both outcomes %HA and %HSD the two curves are shifted against each other. In both models, the variable speed regime was significant (cf. Table 3). This means that, with an average exposure level remaining constant, the proportions of both highly annoyed and highly sleep disturbed were higher in the 50 km/h speed regime. The 30 km/h regime therefore reduced these outcomes irrespective of the average exposure levels. Expressed in dB, this shift of the curves can be determined as the ratio of the unstandardized regression coefficients for the effect of the speed regime to the coefficient for the effect of the exposure level, which results in a shift of 2.18 dB for %HA on the loudest façade and by 3.91 dB for %HSD at the bedroom façade. In a model where %HA is regressed on LDay at the bedroom facade, the shift is even larger, at 4.42 dB. These figures clearly show that in the 30 km/h condition, the percentage of highly annoyed as well as the percentage highly sleep disturbed at the same level is *lower* than during the 50 km/h speed regime. Thus this decrease, obviously, cannot be explained simply by the lower average noise exposure (LDay or LNight

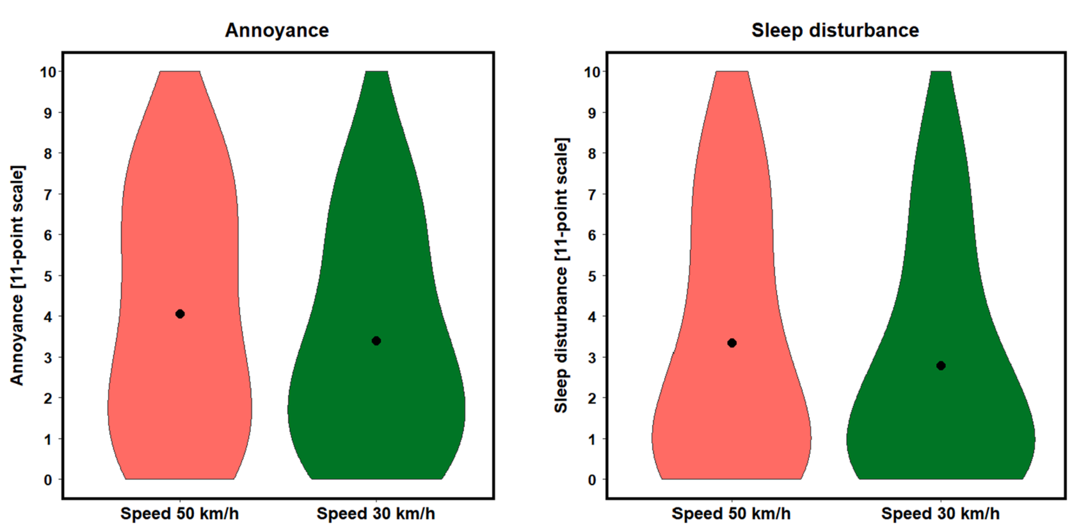

Fig. 5. Density distribution of raw scores for annoyance (5-point ICBEN scale) and noise induced sleep disturbance (11-point scale) in the before (50 km/h) and after (30 km/h) surveys. Violin plots with mean (●).

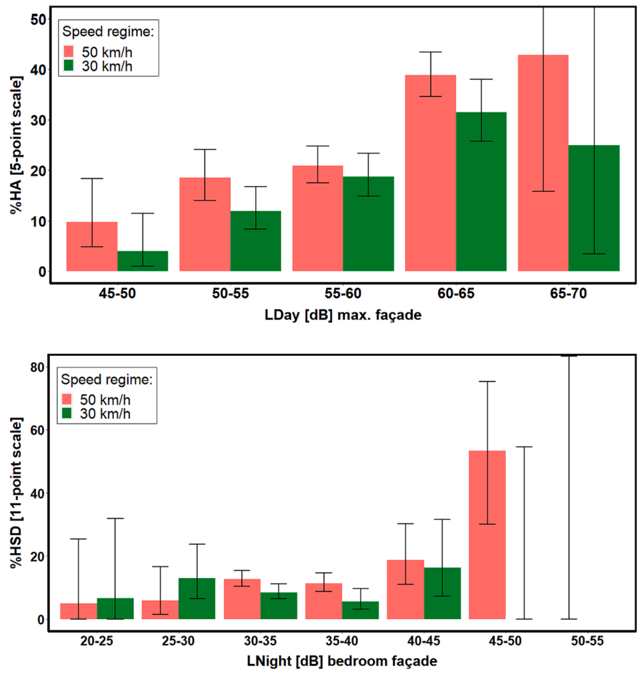

Fig. 6. Percentage of highly annoyed (%HA, top) and highly sleep disturbed (%HSD, bottom) in discrete level categories of LDay and LNight in the before (50 km/h) and after (30 km/h) condition. Whiskers show the Agresti-Coull 95 % confidence interval. Note**.** In the 50–55 dB LNight level category, no one in the 50 km/h condition is HA and there are no data in the 30 km/h condition.

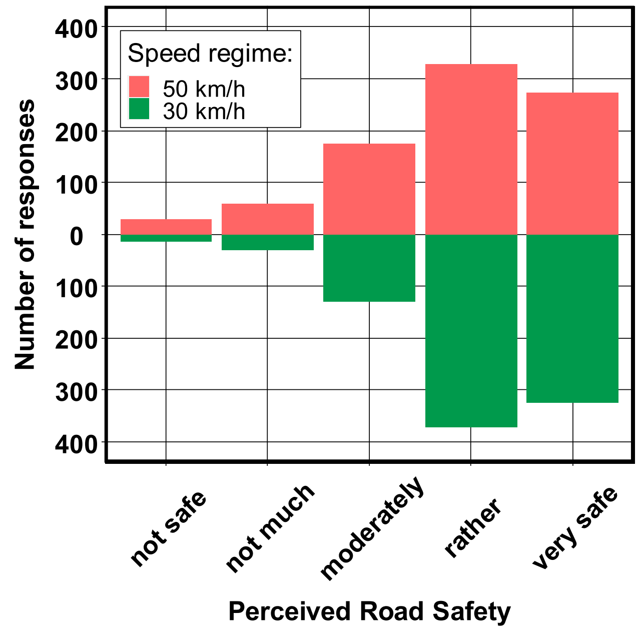

Fig. 7. Mirrored histogram showing the distribution of perceived road safety during the before (50 km/h) and the after-survey (30 km/h).

respectively) in the 30 km/h condition, because the effect of average noise exposure is already accounted for in these models.

3.5. *Effect modification*

In the course of modeling exposure–response relationships, the potential influence of a range of effect modifiers on %HA and %HSD was investigated, namely (1) orientation of bedroom/apartment towards the street, (2) length of residency at the current address, (3) presence or absence of sound proof windows, (4) the time spent on a private outdoor patch (e.g. balcony), (5) the survey stage (A, B1, B2, C, or D).

Survey stage, soundproof windows, and time spent on a private outdoor patch showed no significant modifying effect on either %HA and %HSD. Length of residence was significantly but negatively associated with %HSD. We found a strong significant effect for the orientation of the bedroom towards the nearest street: Fig. 9 below shows that the new speed regime mainly benefitted people whose bedrooms were oriented towards the street or sideways to the street. For persons whose dwelling (or at least whose bedroom) points away from the street (e.g. faces an inner courtyard), the introduction of the new speed limit did not cause a shift in the exposure-relationship relationship. Table 4 lists the parameter estimates for the curves shown in Fig. 9.

3.6. *Investigation of potential bias through weather effects and the COVID-19 pandemic*

Due to various limitations in the practical implementation of the study and due to its partly political character, not all potentially confounding extraneous variables could be completely controlled (cp. Section 4). In particular, it was not possible or appropriate to establish a control group, i.e. a sub-sample without speed regime change (but otherwise identical before and after-surveys). We therefore examined the effect of two particularly relevant and potentially biasing influence

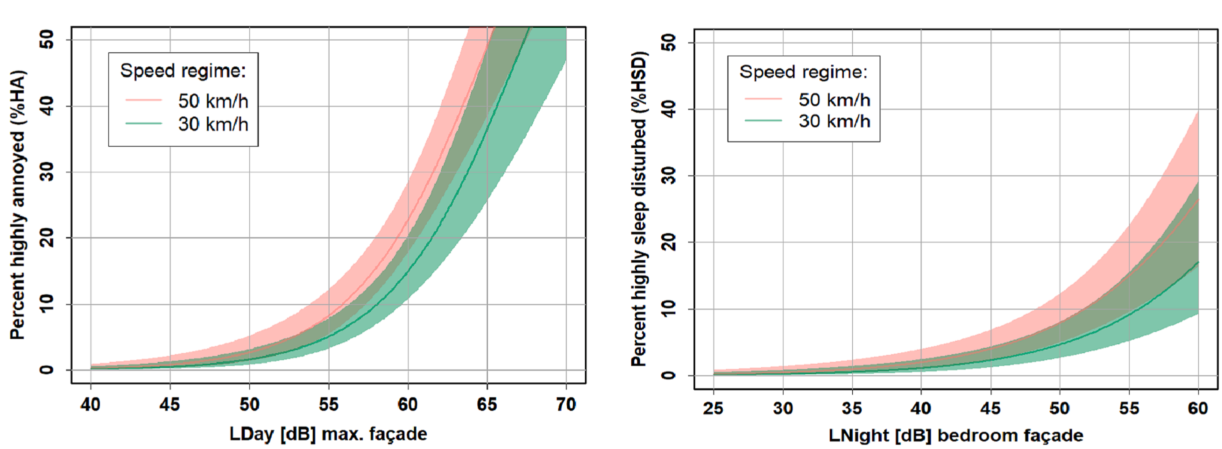

Fig. 8. Exposure-response curves for the percentage highly annoyed (%HA, left) and highly sleep disturbed (%HSD, right) during the speed regime 50 km/h and speed regime 30 km/h (after the changeover). Scales used – Left: 5-point ICBEN scale with cutoff point 60 %; Right: 11-point ICBEN-type scale with cutoff point 73 %. Statistical modelling: Multilevel logistic regression with adjustment for age and sex; plotted are the centered curves (at the mean of age and sex) and the 95 % confidence intervals as shaded areas.

Table 3
Parameter estimates of the multilevel logistic models for %HA regressed on LDay at the loudest façade and %HSD regressed on LNight at the bedroom façade, and further predictors. Legend: B = unstandardized coefficient; SE = standard error of B; VIF = variance inflation factor. Significant p-values are highlighted in bold.

Effect	B	SE	p-value	VIF
Model for percentage highly annoyed (%HA):				
Intercept	−15.6176	1.9451	**<0.01**	0.00
Speed regime 30 km/h (vs 50 km/h)	−0.5173	0.1616	**<0.01**	1.02
LDay (loudest façade point)	0.2373	0.0314	**<0.01**	1.02
Age	0.0016	0.0065	0.80	1.01
Male sex (vs female)	0.1583	0.2260	0.48	1.01
Model for percentage highly sleep disturbed (%HSD):				
Intercept	−8.6125	1.2132	**<0.01**	0.00
Speed regime 30 km/h (vs 50 km/h)	−0.5607	0.2023	**<0.01**	1.00
LNight (bedroom façade)	0.1434	0.0225	**<0.01**	1.02
Age	−0.0169	0.0078	**0.03**	1.01
Male sex (vs female)	−0.2472	0.2646	0.35	1.02

factors, namely temperature at the time of the survey and the COVID-19 pandemic which for some stages already prevailed during the followup survey.

Temperature. It is well known that warmer weather tends to be associated with greater noise annoyance (Brink et al. 2019; Brink et al. 2016; Miedema et al. 2005), most probably due to more outdoor activities in warmer seasons and different window opening behavior. To test the potential weather influence on our results, temperature values within the city limits for each day in the years 2017–2020 were obtained from the Open Data Zurich online platform (Stadt Zürich Open Data, 2021). For each completed valid questionnaire (N = 2177) the average daily temperature between the time of completion and a 30- and 90-day period prior to questionnaire completion was obtained. The mean temperature differences between the before and after-survey waves were + 2.9 (30-day average) and + 3.1 (90-day average) degrees Celsius, respectively. Thus, it was on average warmer during the after-survey whilst the speed regime 30 km/h prevailed. We modeled the effect of the 90-day temperature average on %HA and %HSD using multilevel logistic regression. As the regression results in Table 5 reveal, there was no significant effect of temperature on %HA, but there was a significant positive effect of temperature on the variable %HSD: thus, self-reported sleep disturbance increases – expectedly – with higher temperature, which is a known effect (Caddick et al. 2018). But it is particularly noteworthy that in both models, the coefficient for the temperature effect is positive, i.e. warmer temperatures leading to higher annoyance and sleep disturbance. As the effect of (higher) temperature should undoubtedly *counteract* the observed decrease in annoyance and sleep disturbance, it can be ruled out that the outside temperature had a biasing effect on the results.

COVID-19 pandemic. A part of the after-surveys took place after the onset of the COVID-19 crisis in March 2020. Not only did this crisis lead to a decline in traffic figures in the first half of the year 2020, and hence lower road traffic noise levels, but represented for many such a drastic alteration in living conditions, that it is necessary to examine whether the pandemic situation could also have affected reported annoyance and sleep disturbance in the 30 km/h condition. To investigate this, daily COVID-19 figures (reported new cases, hospitalizations and daily deaths), provided by the Federal Office of Public Health, were linked to questionnaire completion data. Their effect on %HA and %HSD was modeled, alongside speed limit condition and exposure level, again using multilevel logistic regression. Because all before interviews took place prior to the pandemic outbreak, the corresponding figures were set to 0. In the after-surveys, data on the COVID-19 situation were available for 404 persons. Results: Neither for the daily new cases or hospitalizations, nor for the daily deaths, could we find an effect on %HA or %HSD. Subsequently, it was investigated whether the average number of new cases in a 30 or 90 day interval before the respective individual completion date of the questionnaires could have been responsible for a corresponding effect. However, this too could not be confirmed

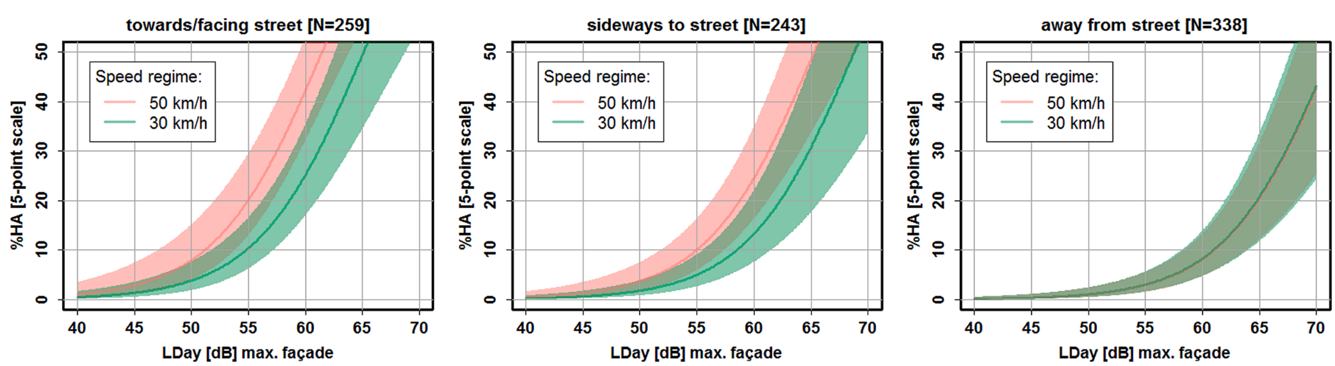

Fig. 9. Exposure-response curves for %HA during the day period for the two speed regimes and bedrooms (dwellings) oriented towards/facing the street (left), pointing sideways to street (middle), or away from the street (right). Statistical modeling: multilevel logistic model with adjustment for age and sex. Plotted are the centered curves (at the mean of age and sex) and the 95% confidence intervals as shaded area.

Table 4
Parameter estimates of the multilevel logistic model for the probability of being highly annoyed (%HA), regressed on LDay at the loudest façade point and additional predictors, with bedroom orientation as an effect modifier. Legend: B = unstandardized coefficient; SE = standard error of B; VIF = variance inflation factor. Significant p-values are highlighted in bold.

Effect	B	SE	p-value	VIF
Intercept	−13.3332	1.9321	**<0.01**	0.00
Speed regime 30 km/h (vs 50 km/h)	−0.7784	0.2610	**<0.01**	1.58
LDay (loudest façade point)	0.2139	0.0314	**<0.01**	1.03
Age	0.0022	0.0066	0.74	1.00
Male sex (vs female)	0.1565	0.2290	0.50	1.01
Bedroom orientation sideways (vs on street)	−0.8124	0.3292	**0.01**	1.19
Bedroom orientation away from street (vs on street)	−2.1235	0.3482	**<0.01**	“
Interaction term: 30 km/h speed regime × orientation sideways	0.0228	0.3928	0.95	1.40
Interaction term: 30 km/h speed regime × orientation away from street	0.8031	0.3854	**0.04**	“

Table 5
Parameter estimates of the multilevel logistic model for the probability of being highly annoyed (%HA) and highly sleep disturbed (%HSD), regressed on LDay at the loudest façade point or LNight at the bedroom façade respectively, and on the average temperature outside over a 90-day period. Legend: B = unstandardized coefficient; SE = standard error of B; VIF = variance inflation factor. Significant p-values are highlighted in bold.

Effect	B	SE	p-value	VIF
Model for percentage highly annoyed (%HA):				
Intercept	−15.7005	1.9792	**<0.01**	0.00
Speed regime 30 km/h (vs 50 km/h)	−0.5443	0.1747	**<0.01**	1.19
LDay (loudest façade point)	0.2330	0.0318	**<0.01**	1.03
Age	0.0014	0.0065	0.83	1.01
Male sex (vs female)	0.1633	0.2244	0.47	1.01
Avg. 90-day temperature	0.0132	0.0227	0.56	1.19
Model for percentage highly sleep disturbed (%HSD):				
Intercept	−9.5041	1.3147	**<0.01**	0.00
Speed regime 30 km/h (vs 50 km/h)	−0.7208	0.2169	**<0.01**	1.15
LNight (bedroom façade)	0.1404	0.0223	**<0.01**	1.02
Age	−0.0175	0.0078	**0.03**	1.01
Male sex (vs female)	−0.2547	0.2638	0.33	1.02
Avg. 90-day temperature	0.0590	0.0288	**0.04**	1.15

statistically. There is therefore no evidence that the COVID-19 pandemic systematically distorted the results of the study.

4. Discussion

4.1. Summary

For the purpose of evaluating the effect of speed reductions from 50 km/h to 30 km/h in the city of Zurich on noise exposure, annoyance and self reported sleep disturbance, an empirical before-after survey and corresponding individual exposure calculations were carried out on a total of 15 street sections. Our study showed a post-changeover decrease of road traffic noise levels at the loudest façade point by an average of 1.6 dB during the day and 1.7 dB at night. This level reduction is within the expected range for an average speed reduction of just under 10 km/h (cf. Table 1). While these values are certainly not very large, noise level reductions of this magnitude can be considered perceptible. In line with the reduced exposure level, we could observe significant reductions of noise annoyance and self-reported sleep disturbance, confirming previous findings about the effects of interventions at source (Brown and van Kamp 2017).

Beyond the global effect of reducing the average exposure, the exposure–response relationships in the lower speed regime were shifted by a few dB toward smaller effects, i.e. lower annoyance and less sleep disturbance. We estimated this effect – depending on the receiver point – to be between about 2 and 4 dB during the day and about 4 dB at night. Thus, at the same average noise level, annoyance and noise induced sleep disturbances were lower at 30 km/h than at 50 km/h.

The outcomes of potentially effect-modifying factors were also examined. Here it was found that especially those residents could benefit from the introduction of the 30 km/h speed limit whose bedrooms were oriented towards the street, while for persons with apartments or bedrooms facing away from the street towards e.g. a backyard, the introduction of the 30 km/h speed limit did not result in an additional reduction of annoyance. No effects biasing the results could be found for both the outside temperature during the respective survey periods and the COVID-19 pandemic (which already prevailed for some of the respondents during followup after the changeover to the speed limit 30 km/h).

4.2. Explanations for the shift of exposure–response curves

An important question to address at this point is, if the beforementioned shift is due to changes of acoustic characteristics as a consequence of lower driving speed (e.g. different level-time courses of passbys, a different acoustic spectrum etc.), or if this shift is rather echoing a so called “change effect”, that typically occurs after more or less abrupt noise level changes. Such change effects have comprehensively been described in the literature (Brown and van Kamp 2009a; Brown and van Kamp 2009b) and basically suggest that when exposure changes, responses of the population to the “new” noise are composed of a normal exposure-related response (such as derivable from steady state exposure–response relationships) and a so called *excess response* that only occurs *because of the change itself* and not because of lower or higher exposure as a consequence of the change. Of course, such excess responses can go in both directions and manifest themselves as an overproportional attenuation (when exposure levels drop) or overproportional increase (when exposure levels rise) of annoyance.

We are inclined to assume that the reasons for the shifted exposure–response curves in our study must have to do with changes in acoustic characteristics that go beyond the mere lowering of the average exposure level, i.e. that other acoustic factors related to the lower driving speed additionally reduce noise annoyance and sleep disturbance. But there could have been alternative mechanisms at work, which are briefly discussed in the following.

- A relatively simple explanation would be to assume, that the respondents reacted unspecifically and positively to the fact that the city authorities have taken care of the improvement of their living environment through the introduction of the speed reduction. We can currently not rule out this explanation.

- As speed reductions not only lead to reduced noise, but also to – as demonstrated here – an increase in perceived road safety, and maybe other accompanying effects such as perception of a more livable neighborhood etc., other than direct noise-related explanations may account for the shift. Such explanations have been termed “surrogate” effects (Brown and van Kamp 2009b). Kastka conjectured in his early study on traffic calming measures in Germany, that car noises were perceived as less annoying because they were less dominant and less threatening after the measures were accomplished (1981). It can thus not be ruled out that this type of change effect could have played a role here.

- The very framing of the survey itself, e.g. in the cover letter, could have triggered a subjective expectancy to be less annoyed under the new speed rule (in the after condition). However, so far, mere expectation has little support as a direct explanation of a change effect (Brown and van Kamp 2009b).

- The longitudinal design with repeated interviewing of the same survey participants could have induced a so called demand response bias, but evidence suggests that such bias generated by repeated questioning is unlikely to be the cause of observed excess-response change effects (Fidell et al. 1985).

The list above is certainly not complete, but covers some of the explanations we regard worthy of consideration. As one can see, the potential explanations brought forward are more or less closely related to each other and it is well possible that none or several such mechanisms act at the same time. It is indeed difficult to objectify which part of the annoyance reduction that we observed can be attributed to effects relating to the nature and intensity of the noise exposure before and after the speed rule change, and which part to a non-acoustic change effect, if at all. Here we need to emphasize that the observation that subjects with dwellings or bedrooms that face away from the street did not show any shift of exposure–response relationship rather speaks for an acoustic explanation and the absence of a (non-acoustic) change effect.

If only acoustic factors play a role for the reduced annoyance/sleep disturbance at the same average exposure level, reasonable candidates for such factors are the lower maximum levels and a less steep slope of rise of level during passbys of vehicles. This explanation is quite straightforward, as both the maximum level and the rise time of the noise level of individual noise events are related to the intensity and probability of reactions to noise, in particular, during sleep (Basner et al. 2011; Brink et al. 2008). Via the same pattern, a lower driving speed also reduces the number of noticeable individual noise events, hence reducing overall annoyance at daytime. This of course too, would make sense as an explanation, and several authors have put forward the assumption that sound has to be noticed in order for it to contribute to annoyance (De Coensel et al. 2009; Schomer and Wagner 1996).

4.3. Strengths and weaknesses

The strengths of the study certainly include the application of a repeated measures design and the comparatively precise calculation of exposure in both the before and after-surveys, especially on the bedroom façade.

On the downside, the lack of a control group (i.e. a sub-sample of persons without speed regime change) in this study must be regarded as a certain disadvantage. With a control group, it could have been examined whether, at best, an unobserved influencing factor could have been held responsible for the decrease in annoyance and sleep disturbance in the after-survey compared to the before-survey (and not the introduction of the new speed limit per se). Possible candidates for such (uncontrollable) influences are political events, media coverage on the topic of reducing speed limits, weather effects, the action of (result-biasing) change effects such as we described above, and other unmeasured and therefore unknown influences (often termed nonacoustic factors). However, there were some underlying conditions during the initiation and planning of the study design that spoke against the implementation of a control group. These were basically the following: (1) (Official) traffic reports for the 30 km/h condition were only conducted on road sections that were affected by the introduction of the new speed regime. Thus, emission level estimates would not have been comparable for a control group during the same time period in terms of data quality and timeliness. (2) The survey participants were addressed directly by the Municipality of Zurich in the cover letter and informed that the survey was conducted in the context of the introduction of the 30 km/h speed limit on their street and that this measure would be evaluated with a followup survey at a later date. With this official appearance, we hoped to increase the response rate, and at the same time it was of course clear that the new speed regime had in fact to be realized. (3) Street sections (and their residents) without speed limit change (for certain reasons) could have differed systematically from those with the change realized, which would not be desirable for a control group. But after all, our analyses of possible biasing effects – some of them mentioned in Section 3.6 – did not indicate any serious overinterpretation of the decrease in annoyance and sleep disturbance due to the lack of a control group. Another inherent weakness this study shares with similar intervention studies is the fact that (1) we don't know for how long the observed annoyance shift will prevail in the population in the future as we estimated the effect of the new speed rule in just one followup survey at one point in time, and (2) we cannot for certain rule out all competing explanations for the observed shift of exposure–response relationships.

5. Conclusions

Empirical studies on noise effects of changes in signalized speed limits are scarce, as the WHO systematic review of intervention studies in noise showed a few years ago: Of the ten "before-after studies" of so-called source interventions referenced in Brown and van Kamp (2017), not a single one concerned speed reductions. Thus, the present study is certainly-one of the few of its kind that used a longitudinal repeated measures design to investigate whether a speed reduction to 30 km/h (from a previous 50 km/h) also results in a reduction of adverse effects of road traffic noise and, most importantly: whether exposure–response relationships differ between the two speed regimes.

The present study clearly showed that city dwellers are relieved from noise by a reduction of the allowed speed to 30 km/h (from a previous 50 km/h) on their residential street by a subsequent reduction of the Leq of 1.6 dB during the day and 1.7 dB at night. After the changeover, also noise annoyance and noise-induced sleep disturbances were reduced in a statistically significant manner, and the perception of road safety increased significantly, although not very markedly. Beyond the global effect of a lower average level (LDay and LNight), the exposure–response relationships between average level and effect shifted by a few dB toward smaller effects, i.e. lower annoyance and less sleep disturbance. We (conservatively) estimate this effect to be at about 2 dB during the day and about 4 dB at night. Thus, at the same average level, annoyance and sleep disturbances were lower at 30 km/h than at 50 km/h. Our study thus provides a convincing argument to push ahead speed limit measures to curb noise pollution.

The present study was conducted on a few municipal roads in the city of Zurich at just two points in time. A future extension of the study to other cities in Switzerland, which is currently in the planning, will include both a control group and a second (and maybe third) followup survey in order to estimate the stability of the effects of speed reductions on the long run, in line with the recommendations of the WHO regarding future research in the domain of noise interventions (WHO 2018).

CRediT authorship contribution statement

Mark Brink: Conceptualization, Methodology, Data curation, Visualization, Writing – original draft. **Simone Mathieu:** Data curation, Writing – review & editing. **Stefanie Rüttener:** Conceptualization, Writing – review & editing.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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