Long-term effects of noise reduction measures on noise annoyance and sleep disturbance: The Norwegian facade insulation study

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The Norwegian facade insulation study includes one pre-intervention and two post-intervention surveys. The facade-insulating measures reduced indoor noise levels by 7 dB on average. Before the intervention, 43% of the respondents were highly annoyed by noise. Half a year after the intervention, the proportion of respondents who were highly annoyed by road traffic noise had been significantly reduced to 15%. The second post-intervention study (2 yr after the first post-intervention study) showed that the proportion of highly annoyed respondents had not changed since the first post-intervention study. The reduction in the respondents' self-reported sleep disturbances (due to traffic noise) also remained relatively stable from the first to the second post-intervention study. In the control group, there were no statistically significant differences in annoyance between the pre-intervention and the two post-intervention studies. Previous studies of traffic changes have reported that people "overreact" to noise changes. This study indicated that when considering a receiver measure, such as facade insulation, the effect of reducing indoor noise levels could be predicted from exposure-response curves based on previous studies. Thus no evidence of an "overreaction" was found.
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I. INTRODUCTION

Road traffic is the primary contributor to environmental noise exposure, and noise impacts health and well-being by causing annoyance, rest, sleep, cognition, and communication disturbances (Berglund *et al.*, 2000; Klæboe *et al.*, 2004; Stansfeld *et al.*, 2005; Muzet, 2007). Sleep disturbances are among the most serious effects of environmental noise (Berglund *et al.* 2000; Fritschi *et al.*, 2011), and one of the most common reasons for noise complaints (Guski, 1977, 1991). Poor sleep is closely linked to anxiety and depression (Neckelmann *et al.*, 2007) and has also been associated with obesity, type 2 diabetes and cardiovascular diseases (Knutson, 2012; Luyster *et al.*, 2012). To date, the long-term consequences of *noise induced* sleep disturbances are still uncertain. However, evidence is mounting that long-term exposure to high levels of transportation noise may increase the risk of hypertension and cardiovascular disease (Bluhm *et al.*, 2007; van Kempen and Babisch, 2012; Sørensen *et al.*, 2012). The World Health Organization (WHO) recently compiled an overview of recent findings about the health impacts of environmental noise (Fritschi *et al.*, 2011).

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Norway is a sparsely populated country, but the majority of the population lives in cities and towns that are densely populated, and noise affects many people in Norway. The main source of noise is road traffic, and 30% of the population is exposed to noise that exceeds 55 dB (Statistics Norway, 2009). Six percent of the Norwegian population states that they are annoyed by noise from road traffic while they are inside their dwellings, and 5% report sleep problems due to noise (Statistics Norway, 2009).

Despite the implementation of noise-abating measures, the number of people exposed to noise levels above 55 dB (from road traffic) has increased by 15% since 1999 (Statistics Norway, 2009). This phenomenon is primarily due to increased traffic and partially due to increased settlement in areas close to the main arterial roads.

A. Background

The failure of noise policies to reduce noise has received significant attention from the Norwegian Department of Transportation and the Department of the Environment. Consequently, noise annoyance reduction targets were established. Part of the motivation for expressing the targets in terms of noise *annoyance* reduction and not *noise* reduction was that annoyance at different noise sources differs even though the nominal noise level is the same. More importantly for noise abatement efforts, new environmental limits were placed on pollution from traffic sources. In particular, a new indoor noise limit of $L_{A,eq,24h}$ 42 dB was imposed, and infrastructure owners became legally responsible for keeping noise under this limit.

As the indoor noise levels in many existing dwellings exceeded the new indoor limit, the Norwegian Public Road Administration began a national effort to install facade sound insulation (including new windows) on approximately 2500 dwellings in 2004 and 2005. Approximately 85% of

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these received improved ventilation in addition to facade insulation and/or new windows, and the majority (96%) received balanced mechanical ventilation.

To evaluate the effect of these measures, a comprehensive set of surveys to evaluate the short- and long-term effects was undertaken. The first part of this evaluation was a quasi-experimental pre- and post-intervention study with a control group, investigating the short-term changes in indoor noise annoyance. For the dwellings in the "experimental" group that received the noise reduction intervention, an average equivalent noise reduction of 7 dB was calculated inside the dwellings. Whereas 42% of the respondents were highly annoyed by indoor noise levels before the intervention, only 16% were still highly annoyed after the noise abatement (Amundsen *et al.*, 2011). The results thus documented that the respondents reacted favorably to the facade insulation and that the measures made substantial improvements in the indoor noise environment.

Previous studies indicate that when changes in noise exposure are achieved by source-related measures (e.g., traffic reductions), the responses could be higher than those predicted from the exposure-response relationships established from a more stable condition (Griffiths and Raw, 1986; Griffins, 1989; Brown and van Kemp, 2009; Kastka *et al.*, 1995), possi- AQ2 bly due to other positive changes influencing the response. Thus in studies where the changes include noise screens or insulation efforts, the change may be smaller than predicted. A review of different theoretical approaches explaining such AQ3 differences can be found in Brown *et al.* (2009).

The observed reductions in noise annoyance after the facade insulation align with what could be expected from the exposure-response curves obtained before the intervention (Amundsen *et al.*, 2011). However, obtaining a short-term reduction similar to what was predicted is no guarantee that this is a lasting improvement. Social intervention studies show that people are often satisfied with an intervention regardless of the result of the intervention (Hawthorne effect). The positive responses in a questionnaire survey short time after the intervention and the "warm glow" from being among the elected in a costly intervention program can be expected to diminish with time. Thus the short-term response could be more favorable than the noise improvements alone would warrant. The study design therefore included a second survey stage, allowing the assessment of the longer-term effects of facade insulation on noise annoyance and sleep disturbances.

B. Objectives

The primary aim of the present study was to examine the long-term effects of facade insulation on annoyance and sleep quality. The short-term effects on indoor annoyance were previously reported by Amundsen *et al.* (2011).

II. METHOD

A. Study design

The study was executed as a pre- and post-intervention study with a control group. The study is quasi-experimental; we could not randomize the individuals into the target and control group. The target group included those residents living in dwellings where the noise level exceeded the Norwegian indoor noise limit of 42 dB. The control group consisted of residents living in dwellings that were considered for inclusion in the governmental scheme but fell short of the inclusion criteria because their indoor noise levels ($L_{A,eq,24h}$) were just below 42 dB. In most cases, the noise levels in the target group barely exceeded the 42 dB criteria and thus, the two groups are assumed to be socio-demographically similar.

The group receiving facade insulation and the control group were both exposed to high noise levels. To establish exposure-response curves, a wider range of exposures was needed, and an additional control group was added in the first and second post-intervention studies. The respondents of this additional control group all lived in areas with low and intermediate noise levels. The respondents were recruited from different parts of Norway.

The noise reduction measures were conducted according to the implementation timelines of the regional offices of the Public Road Directorate. Consequently, the timing of the facade insulation installation was not the same for all respondents. The first and second post-intervention studies were conducted approximately 6 months and 2.5 yr after the implementation of the noise-reducing measures, respectively.

B. Survey and sample

The study consisted of a questionnaire and calculations of outdoor and indoor noise levels for each of the respondents. The pre-intervention study was performed in June 2003/2004, the first post-intervention study was performed in June 2005, and the second post-intervention study was performed in June 2007.

The questionnaires were mailed by post to 1125 of the households that were considered for inclusion in the facade insulation program. These private households were all located along major state roads in different Norwegian counties. The first post-intervention questionnaire was sent to all of the respondents who answered the pre-intervention questionnaire, and the second post-intervention questionnaire was sent to the respondents who answered the first post-intervention questionnaire. An overview of the study populations is shown in Table I.

Some respondents were excluded from the study for three main reasons: Some of the respondents received noise-reducing measures between the first and second post-intervention studies, we lacked noise data for some respondents, and some of the respondents lived in houses that were scheduled to be demolished (due to high noise levels and proximity to major roads).

C. The questionnaire

The questionnaires for the pre- and post-intervention studies contained a common set of core questions assessing the residential noise situation and people's reactions. These questions (for assessing annoyance, sleep disturbances, noise sensitivity, and health impacts from noise) are based on the

TABLE I. Sample characteristics.

	Target group			Control group			Additional control group	
	Pre-intervention	1. post-intervention	2. post-intervention	Pre-intervention	1.post-intervention	2. post-intervention	1. post-intervention	2. post-intervention
No. respondents	169	167	104	231	225	139	111	63
Response rate (%)	57	65	58	57	65	58	28[a]	58
Percentage female	43	44	39	45	46	42	58	60
Age (mean)	54	56	60	56	58	63	51	56

[a]The actual response rate is somewhat higher, but because of the delay between obtaining the sample frame and sending out the questionnaire, some respondents had relocated.

international standardized noise annoyance questions (Fields *et al.*, 2001; ISO/TS 15666:2003, 2003) as well as on experiences obtained from previous socio-acoustic studies undertaken by the Institute of Transport Economics (Klæboe *et al.*, 2004) and by the Norwegian Institute for Public Health (Aasvang *et al.*, 2008). In addition, the post-intervention questionnaire included questions on perceived changes in the noise environment and aspects of the noise-reducing measures themselves (e.g., the type of measure received, perceived improvement, and the resident's satisfaction with the measures, among other factors).

The noise annoyance question used in these analyses was:

"Thinking about the last 12 months, how annoyed were you by noise from road traffic when you were inside your own dwelling?" (five-point response scale from extremely annoyed to not annoyed). [In Norwegian: "Hvis du tenker på det siste året, hvor plaget er du av støy fra vegtrafikken når du er inne i boligen din?" (voldsomt plaget, mye plaget, middels plaget, litt plaget, ikke plaget).]

The following sleep question was used:

"How well do you usually sleep?" (Five-point response scale: Well, rather well, neither well nor badly, rather badly, badly). [In Norwegian: "Hvor godt pleier du vanligvis å sove?" (godt, ganske godt, verken godt eller dårlig, ganske dårlig, dårlig).]

This general sleep question was adopted from the Basic Nordic Sleep Questionnaire (Partinen and Gislason, 1995). The responses were dichotomized, and the two latter responses (*rather badly* or *badly*) indicated poor sleep.

In addition, the following questions were included among the questions on sleep disturbances:

(1) If you have difficulty falling asleep, what might the reasons be?
(2) If you wake up during the night or too early in the morning, what might the reasons be?

Following each of these two questions, a list of several possible reasons for sleep interference was presented. The respondents were asked to indicate one or more of the listed reasons for sleep problems. Embedded among the possible reasons for sleep problems were "I am disturbed by traffic noise" (question 1) and "I wake up because of traffic noise" (question 2). The responses to one or both of these two questions, which indicated sleep disturbances due to traffic noise, were translated into the numerical values that were used as a dependent variable (response/yes = 1, no response = 0) in the statistical analyses. By listing other possible reasons for sleep problems (too much coffee, too hot, pain, bad dreams, stress, etc.) in the questionnaire, we reduced the attention on noise. At the same time, we obtained data on the relative proportions of different self-reported reasons for sleep disturbances (not presented in the current paper). For all of the questions regarding sleep, the time frame employed was the 3 months prior to responding to the questionnaire.

The questionnaire also included questions about indoor air quality, window opening behavior, and annoyance from other noise sources, although responses to these questions are not included in this paper.

D. Noise exposure assessment

The noise exposure from road traffic was calculated as the 24-h equivalent sound pressure level ($L_{A,eq,24h}$). The noise level outside the most exposed facade was calculated using the Nordic Prediction Method (Jonasson *et al.*, 1996). This model adds 3 dB to the free-field noise exposure level to be compatible with measurements taken in front of the facade (which are affected by reflections from the facade). This outcome differs from the European norm in which free-field measurements are utilized. As the night and evening weighting to obtain L_{den} contributes approximately 3 dB to free-field $L_{A,eq,24h}$ values, the Norwegian outdoor $L_{A,eq,24h}$ - values by incident are approximately equal in size to free-field L_{den} values.

Indoor noise level calculations were based on the exposure outside the most exposed facade and the estimated facade sound insulation. The noise level inside was assessed according to Handbook 47 used by the Norwegian Public Road Authorities (Homb and Hveem, 1999). The reduction in the A-weighted sound pressure level from outdoors to indoors is calculated using the weighted sound reduction index (R_W) for each construction element listed (e.g., type of wall, windows) combined with the specific spectrum adaptation term (C) for different noise types as defined in NS-EN ISO 717-1 (Standards Norway, 1997). The calculation assumes closed windows and ventilation inlets.

Before the intervention, residential indoor and outdoor noise levels were calculated for all respondents in both the target group and the control group. In the first post-intervention study, indoor and outdoor noise levels were calculated for the target group only. For the control group, the post-intervention outdoor and indoor noise levels were assumed to have remained the same as they were before the intervention.

Because no second wave calculations were undertaken for the second post-intervention study, one could argue that the accuracy of these noise exposure data was not completely assured (e.g., there may have been significant changes in traffic volume). However, approximately 1 yr after the first post-intervention study was completed, the traffic situation for all of the respondents was reviewed, and the traffic data were inspected for major changes in traffic volume. For all of our respondents, there were negligible changes in traffic recorded compared to the pre-intervention situation. These data support our assumption that the outdoor exposure levels were relatively stable in our study period.

Situations may occur in which temporary large changes in traffic volumes revert back to steady levels, but we are not aware of any sampled areas where this could be the case. There is also the possibility that there has been a change in the level of noise from other sources during the period, but we did not find any indication of such changes in our analysis.

E. Types of analyses performed

1. Changes in indoor annoyance due to facade insulation

To evaluate the efficacy of the facade program in reducing indoor noise levels and indoor noise annoyance due to road traffic, three analyses were conducted.

The first analysis included a simple comparison based on the total number of respondents reporting different degrees of annoyance in the different study periods ($N = 1079$).

Next, we performed a one-way repeated measures analysis of variance (ANOVA between groups) test using the data from the respondents who had answered all three questionnaires ($N = 212$) to check whether the analyses of the panel data yielded similar results when we included all of the respondents in the analysis.

The third analysis consisted of fitting an ordinal logit model with the degree of *indoor* noise annoyance from road traffic as a dependent ordinal variable and road traffic noise exposure *outside* the apartment as a continuous exposure variable. Also included in the analysis were dichotomous variables (a variable coded as one or zero) indicating whether the respondents had received a noise-reducing intervention (yes/no), whether the respondents had experienced an additional long-term effect of having received the intervention (yes/no; comparing the respondents who had received noise-reducing measures in the second post-intervention study to the others), whether the respondents had access to a bedroom on the "quiet" side of the dwelling (yes/no), and self-reports of noise sensitivity (the initial 5-point scale was re-coded as yes/no).

2. Changes in sleep disturbances due to the facade insulation program

Differences in self-reported sleep disturbances due to traffic noise and general sleep quality between the pre-intervention study and the two post-intervention studies were analyzed using McNemar's test. This test assesses the significance of the difference between two dependent proportions. The advantages of this design, in which each subject acts as its own control, are the considerable reduction in inter-subject variability and the exclusion of alternative explanations from possible confounders.

3. Statistical control of modifying factors

Except in the analyses using panel data, we controlled for the following modifying factors: Gender, age, education level, marital status, access to a bedroom on the quiet side of the building, and sensitivity. Access to a bedroom on a "quiet" (less noisy than the most exposed side) side and greater noise sensitivity (self-reported) were the only statistically significant modifying variables.

The sample was examined for changes in the sample composition between the different study periods. The proportion of noise-sensitive respondents was not significantly different between the groups. Approximately 65%–75% of our respondents (depending on group and time) reported that they were sensitive to noise to some degree. Between the target group and the control group (or between the different study periods), there were no statistically significant differences in the percentage of respondents reporting that they had access to a bedroom on the "quiet" side of the building. Approximately 45%–50% of the control group and the target group had access to a bedroom facing the quiet side of the building (compared to 95% of the additional control group).

III. RESULTS

A. Noise reductions

Table II shows the calculated noise levels in the different study periods and study groups. For the target group, the indoor noise level was reduced by an average of 7 dB between the pre-intervention study and the first post-intervention study

TABLE II. Calculated noise levels for each study group for the various survey periods, inside and outside the most exposed facade, in dB ($L_{A,eq,24h}$).

	Target group			Control group			Additional group	
	Pre-intervention	1. post-intervention	2. post-intervention	Pre-intervention	1. post-intervention	2. post-intervention	1. post-intervention	2. post-intervention
Indoor (mean)	43	36	35	39	39	39	16	17
Indoor (min, max)	(39, 49)	(29, 41)	(29,40)	(31, 48)	(30, 43)	(30,43)	(4, 36)	(4, 36)
Outdoor (mean)	71	71	71	69	69	69	46	47
Outdoor (min, max)	(64, 78)	(64, 78)	(64, 78)	(61,76)	(61,74)	(61,74)	(33, 65)	(33, 65)

TABLE III. Noise annoyance inside participants' dwellings, before and after implementation of noise-reducing measures (percentages).

		Annoyed by noise when inside dwelling (%)				
		Extremely	Very	Moderately	Slightly	Not annoyed
Target group	Pre-intervention (N = 161)	11.2	31.7	26.7	17.4	13.0
	1. Post-intervention (N = 152)	2.5	13.4	24.8	31.8	27.4
	2. Post-intervention (N = 99)	0	15.2	22.2	30.3	32.3
Control group	Pre-intervention (N = 210)	5.2	18.4	27.4	25.0	24.1
	1. Post-intervention (N = 203)	6.4	23.0	20.6	27.5	22.5
	2. Post-intervention (N = 120)	8.1	20.3	23.6	25.2	22.8
Additional group	1. Post-intervention (N = 88)	0	1.1	5.7	12.5	80.7
	2. Post-intervention (N = 46)	0	4.3	4.3	8.7	82.6

(reduced from 43 to 36 dB). The mean outdoor noise level was 71 dB in the target group, 69 dB in the control group, and approximately 46 dB in the additional control group.

B. Annoyance

In the target group, approximately 43% of the respondents were highly annoyed (extremely + very) before the intervention, whereas 15%–16% was highly annoyed in the first and second post-intervention periods (see Table III). The difference in annoyance between the period before the intervention and the two post-intervention periods is statistically significant ($P < 0.01$). No significant difference was found in the percentage of highly annoyed respondents between the two post-intervention periods. The percentage of respondents who were highly annoyed did not differ between the different study periods for the control group or for the additional group.

The panel-based repeated ANOVA test including only the respondents who had answered all three questionnaires yielded the same results. The change in annoyance in the target group was significant ($P < 0.0005$) between the pre-intervention study and the two post-intervention studies, whereas the difference between the first and second post-intervention studies was not significant ($P = 0.330$). The multivariate partial eta square was 0.44. In the control group, no significant differences were found between the different study periods.

Table IV shows the parameter estimates for indoor annoyance as a function of noise exposure outside the most exposed side of the dwelling. The effect of having access to a bedroom on the "quiet" side of the building is estimated to be equivalent to a 5.5 dB reduction from the noise level on the most exposed side, and the effect of being noise insensitive (self-reported) is estimated to be equivalent to a 7.5 dB reduction in exposure. The effect of having received a noise-reducing intervention is approximately 6.2 dB, whereas the additional long-term effect of having received facade insulation in the second post-intervention study was not significant.

C. Sleep disturbances

Table V shows the number and percentage of subjects reporting sleep disturbances due to noise as well as poor general sleep in the three studies for the target group, the control group, and the additional low-exposure group.

The proportion of subjects reporting sleep disturbances due to noise in the target group was significantly reduced between the pre-intervention study and the first post-intervention study ($P < 0.0005$, McNemar's test). No significant change ($P = 0.227$) was observed between the two post-intervention studies (Fig. 1). In the control group and the additional group, no significant differences were observed in the proportion of subjects reporting sleep disturbances due to noise between the different studies.

The percentage of respondents reporting poor sleep quality changed from 14.2% to 8.4% in the target group between the pre-intervention study and the first post-intervention study (Table V). This change was statistically significant ($P = 0.011$) (Fig. 2). The percentage of respondents reporting poor sleep quality was unchanged from the first to the second post-intervention study. No statistically significant changes between the studies were observed in the control group or in the additional group (Fig. 2).

TABLE IV. Parameter estimates for a logit model of the degree of noise annoyance when inside the dwelling as a function of the noise level outside the dwellings. Dummies: received intervention, additional effect in the second post-intervention study in the target group, bedroom on the quiet side and noise sensitivity. Norwegian facade insulation study–N = 985.

			95% Confidence interval	
	Estimate	Significance	Lower	Upper
Threshold[a]				
Very annoyed	11.038	***	9.446	12.630
Moderately annoyed	9.074	***	7.510	10.637
Slightly annoyed	7.881	***	6.331	9.430
Not annoyed	6.588	***	5.060	8.116
Location				
$L_{A,eq,24h}$_outdoor	0.126	***	0.104	0.148
Received noise reduction intervention (yes)	−0.781	***	−1.118	−0.444
Additional long term noise effect (yes)	−0.157	n.s	−0.642	0.328
Bedroom on noisy side (no)	−0.695	***	−0.937	−0.453
Noise sensitivity (no)	−0.947	***	−1.206	−0.687

[a]The four threshold groups indicate the threshold between the five different scale categories (see Table III).
***$P < 0.0005$.

TABLE V. Reported sleep disturbances due to road traffic noise and poor sleep in general. Absolute numbers and proportions for all study groups, all stages.

	Target group			Control group			Additional group	
	Pre-intervention N = 155 N (%)	1. Post-intervention N = 154 N (%)	2. Post-intervention N = 96 N (%)	Pre-intervention N = 216 N (%)	1. Post-intervention N = 216 N (%)	2. Post-intervention N = 136 N (%)	1. Post-intervention N = 65 N (%)	2. Post-intervention N = 65 N (%)
Reported sleep disturbance due to traffic noise	70 (45.2)	34 (22.1)	20 (20.8)	69 (31.9)	73 (33.8)	41 (30.1)	6 (7.7)	4 (6.5)
Reported general poor sleep quality	22 (14.2)	13 (8.4)	8 (8.3)	20 (9.3)	22 (10.4)	13 (9.8)	8 (12.5)	7 (11.3)

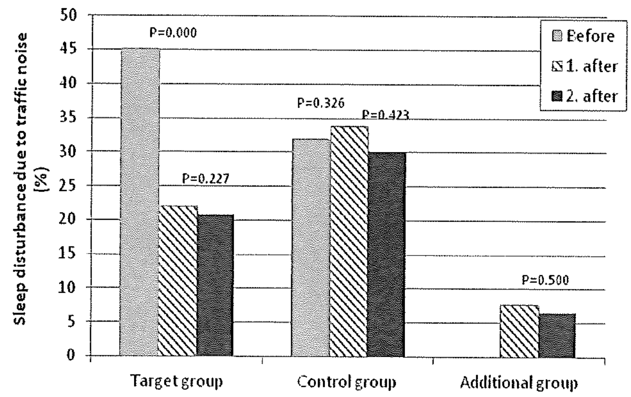

FIG. 1. Proportion of subjects reporting sleep disturbances due to traffic noise before and after facade insulation in the target group, the control group, and the additional low-exposure group. Significance levels (McNemar's test) for the differences between the study results are shown for the different groups.

IV. DISCUSSION

A. The long-term effect on annoyance

Both the panel and cross-sectional analyses on the impact of the intervention indicate that the facade insulation efforts have had a lasting effect in reducing the indoor noise annoyance. In the logit analysis (Table IV), the dummy for the long-term effect is not statistically significant, indicating that there has been a lasting (at least 2-3 yr after the implementation) positive effect on indoor annoyance as a result of the measures. Furthermore, the non-significant increase in the effect is in the opposite direction than it would have been if the short-term effects had been exaggerated.

In the study of the short-term effects (Amundsen *et al.*, 2011), the effects of the facade insulation and the specific measures to reduce indoor noise annoyance were found to be in accordance with what could have been predicted from the exposure-response relationship determined from the data collected in the pre-intervention study. A similar result was also found by Nilsson and Berglund (2006).

We subsequently find little reason to regard the size of the noise annoyance reduction as anything other than a reflection of the real benefits of the facade insulation effort.

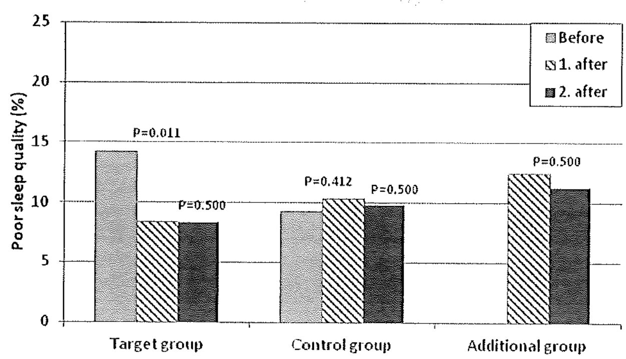

FIG. 2. Proportion of subjects reporting general poor sleep quality before and after facade insulation in the target group, the control group, and the additional low-exposure group. Significance levels (McNemar's test) for the differences between the study results are shown for the different groups.

In the control group, the annoyance levels remained more or less at the same level throughout the entire study period. There was a slight (but not significant) increase from 24% to 29% in the proportion of respondents who were highly annoyed (extremely + very) between the pre-intervention study and the first post-intervention study (see Table III), but this proportion had stabilized by the second post-intervention study. The slight increase in annoyance between the pre-intervention period and the first post-intervention study could be a result of the fact that the respondents who stated that they were sensitive to noise were more likely to answer the follow-up questionnaires. Furthermore, some of the respondents in the pre-intervention study might have known that their dwellings were considered for facade insulation, and they may have reacted with disappointment to the news that they were excluded from the program. This sentiment might also have contributed to the slight increase in annoyance in the control group. Unfortunately, we had no information about which and how many of the respondents in the control group knew they were considered for noise reduction.

B. Sleep disturbances and possible long-term effects

The proportion of subjects reporting sleep disturbances due to noise as well as the proportion reporting poor sleep in general was significantly reduced in the target group after the noise abatement. Not surprisingly, the effect of facade insulation was largest on the response to the question about sleep disturbances due to noise. However, the proportion of subjects reporting poor sleep in general was also considerably reduced after the facade improvements, indicating that the intervention also had a positive effect on overall perceived sleep quality. Neither sleep measure in the second post-intervention study produced significantly different results from the first post-intervention study, indicating a lasting effect of improved subjective sleep. To the best of our knowledge, only a few previous studies reported effects on sleep due to changes in traffic noise exposure (Öhrström, 2004; Öhrström and Björkman, 1983; Vallet *et al.*, 1983), and our results align with the previous results. Our results provide further evidence that nocturnal noise reduction significantly improves subjective sleep quality and also indicate that people do not fully adapt to nocturnal noise.

C. Noise calculations

The indoor and outdoor noise levels for all dwellings were calculated just prior to the pre-intervention study. The indoor noise levels were re-calculated in the target group after the noise-reducing measures were implemented. The consultants performing the noise calculations are generally conservative in their calculations, and control measurements from several of the dwellings confirmed this (see also Amundsen *et al.*, 2011).

We were not able to obtain updated measurements of outdoor noise levels for the first and second post-intervention studies. However, to obtain some indication of the validity of the data, we asked the Norwegian Public Roads Administration to determine if there had been any major traffic changes in the areas included in our study. No major changes in traffic volume were reported. Minor changes in traffic density, diurnal distribution, and the types of vehicles may have occurred. However, noise levels remain relatively stable as traffic increases (e.g., a 26% change in traffic density equals a change of ±1 dB). The fact that there were no statistically significant differences in reported indoor annoyance between the different study periods in the control or the supplementary sample or between the first and second post-intervention studies in the target group supports the assumption that there have been no major changes in the outdoor noise level during the study period.

We only had access to $L_{A,eq,24h}$ calculations; thus, we could not evaluate the effect of possible changes in maximum values or L_{night} on annoyance or sleep disturbances. Previous studies indicate that sleep disturbances are affected more by changes in the maximum noise level than the average noise level (Wilkinson and Campbell, 1984; Tulen *et al.*, 1986; Laszlo *et al.*, 2012). After the improvements of the facades and windows, $L_{AF,max}$ as well as L_{night} were reduced, but we could not estimate the magnitude of the effect associated with the reduction in these noise parameters. Furthermore, we did not have access to noise levels on the "quiet" side of the dwellings. However, all respondents were asked if their bedrooms faced a "quiet" side and whether this "quiet" side consisted of a courtyard, a private garden or a street with little traffic. The responses to this question were used as a covariate in our analysis.

V. CONCLUSION

An outdoor noise level lower than 55 dB $L_{A,eq,16h}$ is recommended by the WHO (Berglund *et al.*, 1999) to protect the population from serious annoyance. Our target group was exposed to an average of 71 dB $L_{A,eq,24h}$ (outside of the most exposed facade),and the control group to an average of 69 dB $L_{A,eq,24h}$. As expected, a high percentage of our study group participants were still highly annoyed by traffic noise. In the target group, however, facade insulation had a substantial and seemingly lasting positive effect on indoor noise annoyance and sleep quality.

To further reduce annoyance and sleep disturbances for people living in areas with high outdoor noise levels, reducing the noise level by implementing at-source measures and/or implementing measures to reduce nighttime noise should be considered. This strategy will enable residents to have their windows open and still maintain a tolerable level of indoor noise.

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