

1 Long-term effects of noise reduction measures on noise 2 annoyance and sleep disturbance: The Norwegian facade 3 insulation study

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9
10 The Norwegian facade insulation study includes one pre-intervention and two post-intervention sur-
11 veys. The facade-insulating measures reduced indoor noise levels by 7 dB on average. Before the
12 intervention, 43% of the respondents were highly annoyed by noise. Half a year after the interven-
13 tion, the proportion of respondents who were highly annoyed by road traffic noise had been signifi-
14 cantly reduced to 15%. The second post-intervention study (2 yr after the first post-intervention
15 study) showed that the proportion of highly annoyed respondents had not changed since the first
16 post-intervention study. The reduction in the respondents' self-reported sleep disturbances (due to
17 traffic noise) also remained relatively stable from the first to the second post-intervention study. In
18 the control group, there were no statistically significant differences in annoyance between the pre-
19 intervention and the two post-intervention studies. Previous studies of traffic changes have reported
20 that people "overreact" to noise changes. This study indicated that when considering a receiver mea-
21 sure, such as facade insulation, the effect of reducing indoor noise levels could be predicted from ex-
22 posure-response curves based on previous studies. Thus no evidence of an "overreaction" was found.
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25 I. INTRODUCTION

26 Road traffic is the primary contributor to environmental
27 noise exposure, and noise impacts health and well-being by
28 causing annoyance, rest, sleep, cognition, and communication
29 disturbances (Berglund *et al.*, 2000; Klæboe *et al.*, 2004;
30 Stansfeld *et al.*, 2005; Muzet, 2007). Sleep disturbances are
31 among the most serious effects of environmental noise
32 (Berglund *et al.* 2000; Fritschi *et al.*, 2011), and one of the
33 most common reasons for noise complaints (Guski, 1977,
34 1991). Poor sleep is closely linked to anxiety and depression
35 (Neckelmann *et al.*, 2007) and has also been associated with
36 obesity, type 2 diabetes and cardiovascular diseases
37 (Knutson, 2012; Luyster *et al.*, 2012). To date, the long-term
38 consequences of *noise induced* sleep disturbances are still
39 uncertain. However, evidence is mounting that long-term ex-
40 posure to high levels of transportation noise may increase the
41 risk of hypertension and cardiovascular disease (Bluhm *et al.*,
42 2007; van Kempen and Babisch, 2012; Sørensen *et al.*,
43 2012). The World Health Organization (WHO) recently com-
44 piled an overview of recent findings about the health impacts
45 of environmental noise (Fritschi *et al.*, 2011).

46 Norway is a sparsely populated country, but the majority
47 of the population lives in cities and towns that are densely
48 populated, and noise affects many people in Norway. The
49 main source of noise is road traffic, and 30% of the popula-
50 tion is exposed to noise that exceeds 55 dB (Statistics

Norway, 2009). Six percent of the Norwegian population
51 states that they are annoyed by noise from road traffic while
52 they are inside their dwellings, and 5% report sleep problems
53 due to noise (Statistics Norway, 2009).
54

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

61 A. Background

62 The failure of noise policies to reduce noise has received
63 significant attention from the Norwegian Department of
64 Transportation and the Department of the Environment.
65 Consequently, noise annoyance reduction targets were estab-
66 lished. Part of the motivation for expressing the targets in
67 terms of noise *annoyance* reduction and not *noise* reduction
68 was that annoyance at different noise sources differs even
69 though the nominal noise level is the same. More importantly
70 for noise abatement efforts, new environmental limits were
71 placed on pollution from traffic sources. In particular, a new
72 indoor noise limit of $L_{A,eq,24h}$ 42 dB was imposed, and infra-
73 structure owners became legally responsible for keeping
74 noise under this limit.

75 As the indoor noise levels in many existing dwellings
76 exceeded the new indoor limit, the Norwegian Public Road
77 Administration began a national effort to install facade
78 sound insulation (including new windows) on approximately
79 2500 dwellings in 2004 and 2005. Approximately 85% of

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

83 To evaluate the effect of these measures, a comprehen-
 84 sive set of surveys to evaluate the short- and long-term
 85 effects was undertaken. The first part of this evaluation was
 86 a quasi-experimental pre- and post-intervention study with a
 87 control group, investigating the short-term changes in indoor
 88 noise annoyance. For the dwellings in the “experimental”
 89 group that received the noise reduction intervention, an aver-
 90 age equivalent noise reduction of 7 dB was calculated inside
 91 the dwellings. Whereas 42% of the respondents were highly
 92 annoyed by indoor noise levels before the intervention, only
 93 16% were still highly annoyed after the noise abatement
 94 (Amundsen *et al.*, 2011). The results thus documented that
 95 the respondents reacted favorably to the facade insulation
 96 and that the measures made substantial improvements in the
 97 indoor noise environment.

98 Previous studies indicate that when changes in noise ex-
 99 posure are achieved by source-related measures (e.g., traffic
 100 reductions), the responses could be higher than those predicted
 101 from the exposure-response relationships established from a
 102 more stable condition (Griffiths and Raw, 1986; Griffins,
 103 1989; Brown and van Kemp, 2009; Kastka *et al.*, 1995), possi-
 104 bly due to other positive changes influencing the response.
 105 Thus in studies where the changes include noise screens or
 106 insulation efforts, the change may be smaller than predicted.
 107 A review of different theoretical approaches explaining such
 108 differences can be found in Brown *et al.* (2009).

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

126 **B. Objectives**

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

131 **II. METHOD**

132 **A. Study design**

133 The study was executed as a pre- and post-intervention
 134 study with a control group. The study is quasi-experimental;

we could not randomize the individuals into the target and 135
 control group. The target group included those residents liv- 136
 ing in dwellings where the noise level exceeded the 137
 Norwegian indoor noise limit of 42 dB. The control group 138
 consisted of residents living in dwellings that were consid- 139
 ered for inclusion in the governmental scheme but fell short 140
 of the inclusion criteria because their indoor noise levels 141
 ($L_{A,eq,24h}$) were just below 42 dB. In most cases, the noise 142
 levels in the target group barely exceeded the 42 dB criteria 143
 and thus, the two groups are assumed to be socio- 144
 demographically similar. 145

The group receiving facade insulation and the control 146
 group were both exposed to high noise levels. To establish 147
 exposure-response curves, a wider range of exposures was 148
 needed, and an additional control group was added in the 149
 first and second post-intervention studies. The respondents 150
 of this additional control group all lived in areas with low 151
 and intermediate noise levels. The respondents were 152
 recruited from different parts of Norway. 153

The noise reduction measures were conducted according 154
 to the implementation timelines of the regional offices of the 155
 Public Road Directorate. Consequently, the timing of the fa- 156
 cade insulation installation was not the same for all respond- 157
 ents. The first and second post-intervention studies were 158
 conducted approximately 6 months and 2.5 yr after the imple- 159
 mentation of the noise-reducing measures, respectively. 160

161 **B. Survey and sample**

The study consisted of a questionnaire and calculations 162
 of outdoor and indoor noise levels for each of the respond- 163
 ents. The pre-intervention study was performed in June 164
 2003/2004, the first post-intervention study was performed 165
 in June 2005, and the second post-intervention study was 166
 performed in June 2007. 167

The questionnaires were mailed by post to 1125 of the 168
 households that were considered for inclusion in the facade 169
 insulation program. These private households were all 170
 located along major state roads in different Norwegian coun- 171
 ties. The first post-intervention questionnaire was sent to all 172
 of the respondents who answered the pre-intervention ques- 173
 tionnaire, and the second post-intervention questionnaire 174
 was sent to the respondents who answered the first post- 175
 intervention questionnaire. An overview of the study popula- 176
 tions is shown in Table I. 177

Some respondents were excluded from the study for 178
 three main reasons: Some of the respondents received 179
 noise-reducing measures between the first and second post- 180
 intervention studies, we lacked noise data for some respond- 181
 ents, and some of the respondents lived in houses that were 182
 scheduled to be demolished (due to high noise levels and 183
 proximity to major roads). 184

185 **C. The questionnaire**

The questionnaires for the pre- and post-intervention 186
 studies contained a common set of core questions assessing 187
 the residential noise situation and people’s reactions. These 188
 questions (for assessing annoyance, sleep disturbances, noise 189
 sensitivity, and health impacts from noise) are based on the 190

AQ2

AQ3

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

^aThe 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.

191 international standardized noise annoyance questions (Fields
192 *et al.*, 2001; ISO/TS 15666:2003, 2003) as well as on experi-
193 ences obtained from previous socio-acoustic studies under-
194 taken by the Institute of Transport Economics (Klæboe
195 *et al.*, 2004) and by the Norwegian Institute for Public
196 Health (Aasvang *et al.*, 2008). In addition, the post-
197 intervention questionnaire included questions on perceived
198 changes in the noise environment and aspects of the noise-
199 reducing measures themselves (e.g., the type of measure
200 received, perceived improvement, and the resident's satisfac-
201 tion with the measures, among other factors).

202 The noise annoyance question used in these analyses
203 was:

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

211 The following sleep question was used:

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

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

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

223 (1) If you have difficulty falling asleep, what might the rea-
224 sons be?

225 (2) If you wake up during the night or too early in the morn-
226 ing, what might the reasons be?

227 Following each of these two questions, a list of several
228 possible reasons for sleep interference was presented. The
229 respondents were asked to indicate one or more of the listed
230 reasons for sleep problems. Embedded among the possible
231 reasons for sleep problems were "I am disturbed by traffic
232 noise" (question 1) and "I wake up because of traffic noise"
233 (question 2). The responses to one or both of these two ques-
234 tions, which indicated sleep disturbances due to traffic noise,

235 were translated into the numerical values that were used as a
236 dependent variable (response/yes = 1, no response = 0) in the
237 statistical analyses. By listing other possible reasons for sleep
238 problems (too much coffee, too hot, pain, bad dreams, stress,
239 etc.) in the questionnaire, we reduced the attention on noise.
240 At the same time, we obtained data on the relative propor-
241 tions of different self-reported reasons for sleep disturbances
242 (not presented in the current paper). For all of the questions
243 regarding sleep, the time frame employed was the 3 months
244 prior to responding to the questionnaire.

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

D. Noise exposure assessment 249

250 The noise exposure from road traffic was calculated as
251 the 24-h equivalent sound pressure level ($L_{A,eq,24h}$). The noise
252 level outside the most exposed facade was calculated using
253 the Nordic Prediction Method (Jonasson *et al.*, 1996). This
254 model adds 3 dB to the free-field noise exposure level to be
255 compatible with measurements taken in front of the facade
256 (which are affected by reflections from the facade). This out-
257 come differs from the European norm in which free-field
258 measurements are utilized. As the night and evening weight-
259 ing to obtain L_{den} contributes approximately 3 dB to free-field
260 $L_{A,eq,24h}$ values, the Norwegian outdoor $L_{A,eq,24h}$ - values by
261 incident are approximately equal in size to free-field L_{den}
262 values.

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

275 Before the intervention, residential indoor and outdoor
276 noise levels were calculated for all respondents in both the tar-
277 get group and the control group. In the first post-intervention

278 study, indoor and outdoor noise levels were calculated for the
 279 target group only. For the control group, the post-intervention
 280 outdoor and indoor noise levels were assumed to have
 281 remained the same as they were before the intervention.

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

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

300 **E. Types of analyses performed**

301 **1. Changes in indoor annoyance due to facade**
 302 **insulation**

303 To evaluate the efficacy of the facade program in reduc-
 304 ing indoor noise levels and indoor noise annoyance due to
 305 road traffic, three analyses were conducted.

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

309 Next, we performed a one-way repeated measures anal-
 310 ysis of variance (ANOVA between groups) test using the
 311 data from the respondents who had answered all three ques-
 312 tionnaires (N = 212) to check whether the analyses of the
 313 panel data yielded similar results when we included all of
 314 the respondents in the analysis.

315 The third analysis consisted of fitting an ordinal logit
 316 model with the degree of *indoor* noise annoyance from road
 317 traffic as a dependent ordinal variable and road traffic noise
 318 exposure *outside* the apartment as a continuous exposure vari-
 319 able. Also included in the analysis were dichotomous varia-
 320 bles (a variable coded as one or zero) indicating whether the
 321 respondents had received a noise-reducing intervention (yes/
 322 no), whether the respondents had experienced an additional
 323 long-term effect of having received the intervention (yes/no;

comparing the respondents who had received noise-reducing 324
 measures in the second post-intervention study to the others), 325
 whether the respondents had access to a bedroom on the 326
 “quiet” side of the dwelling (yes/no), and self-reports of noise 327
 sensitivity (the initial 5-point scale was re-coded as yes/no). 328

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

331 Differences in self-reported sleep disturbances due to
 332 traffic noise and general sleep quality between the pre-
 333 intervention study and the two post-intervention studies were
 334 analyzed using McNemar’s test. This test assesses the signifi-
 335 cance of the difference between two dependent proportions.
 336 The advantages of this design, in which each subject acts as
 337 its own control, are the considerable reduction in inter-
 338 subject variability and the exclusion of alternative explana-
 339 tions from possible confounders.

340 **3. Statistical control of modifying factors**

341 Except in the analyses using panel data, we controlled
 342 for the following modifying factors: Gender, age, education
 343 level, marital status, access to a bedroom on the quiet side of
 344 the building, and sensitivity. Access to a bedroom on a
 345 “quiet” (less noisy than the most exposed side) side and
 346 greater noise sensitivity (self-reported) were the only statisti-
 347 cally significant modifying variables.

348 The sample was examined for changes in the sample
 349 composition between the different study periods. The propor-
 350 tion of noise-sensitive respondents was not significantly dif-
 351 ferent between the groups. Approximately 65%–75% of our
 352 respondents (depending on group and time) reported that they
 353 were sensitive to noise to some degree. Between the target
 354 group and the control group (or between the different study
 355 periods), there were no statistically significant differences in
 356 the percentage of respondents reporting that they had
 357 access to a bedroom on the “quiet” side of the building.
 358 Approximately 45%–50% of the control group and the target
 359 group had access to a bedroom facing the quiet side of the
 360 building (compared to 95% of the additional control group).

361 **III. RESULTS**

362 **A. Noise reductions**

363 Table II shows the calculated noise levels in the different
 364 study periods and study groups. For the target group, the
 365 indoor noise level was reduced by an average of 7 dB between
 366 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,cq,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.

	Estimate	Significance	95% Confidence interval	
			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

^aThe 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	
	1. Post-intervention N = 155 N (%)	2. Post-intervention N = 96 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)	20 (20.8)	69 (31.9)	41 (30.1)	6 (7.7)	4 (6.5)
Reported general poor sleep quality	22 (14.2)	8 (8.3)	20 (9.3)	13 (9.8)	8 (12.5)	7 (11.3)

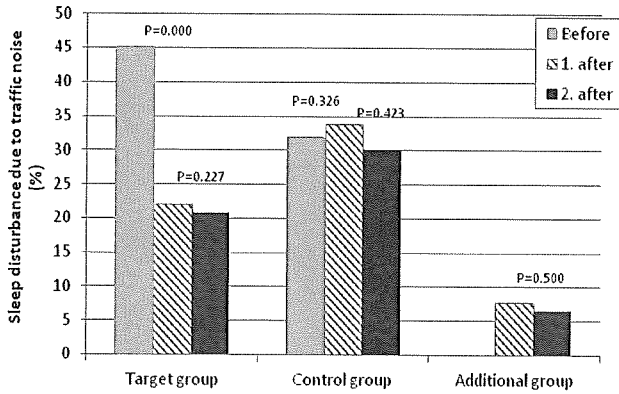


FIG. 1. Proportion of subjects reporting sleep disturbances due to traffic noise before and after facade insulation in the target group, the control group, and the additional low-exposure group. Significance levels (McNemar's test) for the differences between the study results are shown for the different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

426 **IV. DISCUSSION**

427 **A. The long-term effect on annoyance**

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

438 In the study of the short-term effects (Amundsen *et al.*,
 439 2011), the effects of the facade insulation and the specific
 440 measures to reduce indoor noise annoyance were found to be
 441 in accordance with what could have been predicted from the
 442 exposure-response relationship determined from the data
 443 collected in the pre-intervention study. A similar result was
 444 also found by Nilsson and Berglund (2006).

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

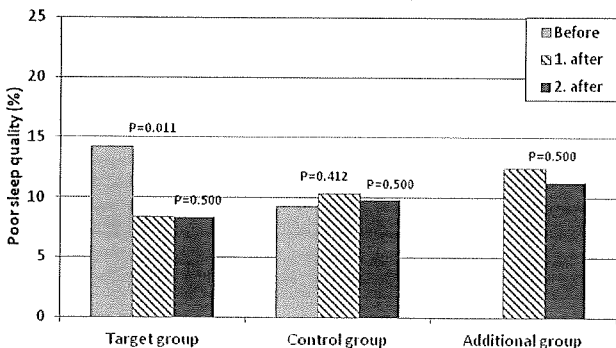


FIG. 2. Proportion of subjects reporting general poor sleep quality before and after facade insulation in the target group, the control group, and the additional low-exposure group. Significance levels (McNemar's test) for the differences between the study results are shown for the different groups.

In the control group, the annoyance levels remained
 more or less at the same level throughout the entire study pe-
 riod. 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 respond-
 ents 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.

468 **B. Sleep disturbances and possible long-term effects**

469 The proportion of subjects reporting sleep disturbances
 470 due to noise as well as the proportion reporting poor sleep
 471 in general was significantly reduced in the target group af-
 472 ter the noise abatement. Not surprisingly, the effect of fa-
 473 cade insulation was largest on the response to the question
 474 about sleep disturbances due to noise. However, the propor-
 475 tion of subjects reporting poor sleep in general was also
 476 considerably reduced after the facade improvements, indi-
 477 cating that the intervention also had a positive effect on
 478 overall perceived sleep quality. Neither sleep measure in
 479 the second post-intervention study produced significantly
 480 different results from the first post-intervention study, indi-
 481 cating a lasting effect of improved subjective sleep. To the
 482 best of our knowledge, only a few previous studies reported
 483 effects on sleep due to changes in traffic noise exposure
 484 (Öhrstöm, 2004; Öhrström and Björkman, 1983; Vallet
 485 *et al.*, 1983), and our results align with the previous results.
 486 Our results provide further evidence that nocturnal noise
 487 reduction significantly improves subjective sleep quality
 488 and also indicate that people do not fully adapt to nocturnal
 489 noise.

490 **C. Noise calculations**

491 The indoor and outdoor noise levels for all dwellings
 492 were calculated just prior to the pre-intervention study. The
 493 indoor noise levels were re-calculated in the target group af-
 494 ter the noise-reducing measures were implemented. The con-
 495 sultants performing the noise calculations are generally
 496 conservative in their calculations, and control measurements
 497 from several of the dwellings confirmed this (see also
 498 Amundsen *et al.*, 2011).

499 We were not able to obtain updated measurements of
 500 outdoor noise levels for the first and second post-
 501 intervention studies. However, to obtain some indication of
 502 the validity of the data, we asked the Norwegian Public
 503 Roads Administration to determine if there had been any

504 major traffic changes in the areas included in our study. No
 505 major changes in traffic volume were reported. Minor
 506 changes in traffic density, diurnal distribution, and the types
 507 of vehicles may have occurred. However, noise levels
 508 remain relatively stable as traffic increases (e.g., a 26%
 509 change in traffic density equals a change of ± 1 dB). The fact
 510 that there were no statistically significant differences in
 511 reported indoor annoyance between the different study peri-
 512 ods in the control or the supplementary sample or between
 513 the first and second post-intervention studies in the target
 514 group supports the assumption that there have been no major
 515 changes in the outdoor noise level during the study period.

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

532 V. CONCLUSION

533 An outdoor noise level lower than 55 dB $L_{A,eq,16h}$ is rec-
 534 ommended by the WHO (Berglund *et al.*, 1999) to protect
 535 the population from serious annoyance. Our target group
 536 was exposed to an average of 71 dB $L_{A,eq,24h}$ (outside of the
 537 most exposed facade), and the control group to an average of
 538 69 dB $L_{A,eq,24h}$. As expected, a high percentage of our study
 539 group participants were still highly annoyed by traffic noise.
 540 In the target group, however, facade insulation had a sub-
 541 stantial and seemingly lasting positive effect on indoor noise
 542 annoyance and sleep quality.

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

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