RESEARCH ARTICLE

Maternal occupational noise exposure during pregnancy and children's early language acquisition

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Abstract

Introduction

Noise exposure during pregnancy may affect a child's auditory system, which may disturb
fetal learning and language development. We examined the impact of occupational noise
exposure during pregnancy on children's language acquisition at the age of one.

Methods

A cohort study was conducted among women working in the food industry, as kindergarten
teachers, musicians, dental nurses, or pharmacists who had a child aged ≤1 year. The anal-
yses covered 408 mother-child pairs. Language acquisition was measured using the Infant-
Toddler Checklist. An occupational hygienist assessed noise exposure individually as no (N
= 180), low (70–78 dB; N = 108) or moderate/high exposure (≥79 dB; N = 120).

Results

Among the boys, the adjusted mean differences in language acquisition scores were -0.4
(95% CI -2.5, 1.8) for low, and -0.7 (95% CI -2.9, 1.4) for moderate/high exposure compared
to no exposure. Among the girls the respective scores were +0.1 (95% CI -2.2, 2.5) and -0.1
(95% CI -2.3, 2.2). Among the children of kindergarten teachers, who were mainly exposed
to human noise, low or moderate exposure was associated with lower language acquisition
scores. The adjusted mean differences were -3.8 (95% CI -7.2, -0.4) for low and -4.9 (95%
CI -8.6, -1.2) for moderate exposure.

Conclusions

In general, we did not detect an association between maternal noise exposure and chil-
dren's language acquisition among one-year-old children. However, the children of

kindergarten teachers exposed to human noise had lower language acquisition scores than the children of the non-exposed participants. These suggestive findings merit further investigation by level and type of exposure.

Introduction

Noise is known to penetrate the tissues and fluids surrounding the fetal head and to stimulate the inner ear through bone conduction. The abdominal wall and uterus attenuate some noises, allowing the fetus to hear predominately low-frequency sounds. High-frequency sounds in turn are greatly attenuated by the abdomen [1,2].

Environmental factors play an important role in the development of a child's auditory processing and language acquisition. Auditory processing develops early, and fetuses are able to discriminate between the sounds that they hear [3].

Studies of rats have shown that compared to music, prenatal noise weakens brain development and therefore possibly also the development of the auditory system [4,5].

Findings among humans have indicated delays in the language development of prematurely born infants who have spent their first weeks (last trimester) in the sound environment of neonatal intensive care units. Some researchers have proposed that these delays could partially be related to differences in the sound environment, as these units typically offer more machine-like sounds than language-related sounds [6–8].

A study of neonates has shown that acoustic noise changes the processing of sounds in the brain [9]. Another study has revealed that compared to silence, short-term exposure of two-year-old children to acoustic noise affects the brain processes related to sound processing [10]. This may in turn affect a child's language acquisition, and possibly lead to a weakened ability to learn concepts [11], which is detrimental to the overall ability to learn. Such damage might limit a child's ability to study, graduate and build a successful career as an adult.

Several environmental factors have been observed as affecting a child's language acquisition. During the first year, children usually learn to comprehend words and speech, and to use the sounds they hear in their babbling and their first words [12]. Listening to music and a mother's story-telling supports language acquisition, whereas background noise and the insensitiveness of a mother have been linked to delayed language acquisition [13–17]. Neurally, noise degrades central auditory processing [18], which is fundamental for language acquisition [11,12]. Delayed early language acquisition is a substantial risk factor for later language impairment [19].

The findings regarding the effect of prenatal noise exposure on hearing impairments among children have been conflicting. Two early reports [20,21] associated maternal exposure to high noise levels (85–95 dB or >100 dB) with hearing deterioration among children, but the studies were based on small samples and therefore had low precision. A later study [22] indicated no hearing impairment after exposure (>80 but <90 dB) but presented unspecific inclusion criteria. A recently published study [23], however, showed an association between occupational noise exposure (>85 dB) during pregnancy and hearing dysfunction among children.

We hypothesized that regular exposure to noise during pregnancy might affect the fetal auditory system in ways that could influence language development. Thus, the aim of our study was to investigate the potential impact of a mother's occupational noise exposure during pregnancy on the language acquisition of her child. We investigated whether prenatal

exposures to industrial noise, high frequency noise in dental clinics, human noise in kinder-gartens, and musical sounds in musicians' work affect children's language acquisition at the age of one. The impact of maternal noise exposure during pregnancy on a child's language acquisition has not been studied previously.

Material and methods

Participants and data collection procedure

The study population consisted of Finnish mothers working in sectors with or without occupational noise exposure and their children born between April 2013 and March 2014. We focused on occupational branches in which exposure to various types of noise was known to be present, and in which documented information on the range of noise or sound level in Finnish workplaces was available. Pharmacists were selected as the non-exposed control group. In Finland, 70% of working aged women were members of a trade union in 2013 (Ministry of Employment and the Economy). We identified 17 138 women at a fertile age of 18–45 from the members of five trade unions: kindergarten teachers (N = 3900), food industry workers (N = 6395), musicians (N = 937), dental nurses (N = 3283), and pharmacists (N = 2623). Using the personal identity codes of the women, we collected the data (birth date, gender, native language) on their children (singletons) between the ages of 6 weeks and 11 months from the Population Register Centre. On the mother, we collected the following information: native language, address, and ages of all biological children. We restricted the population to Finnish-speaking mothers, and obtained data on 187 kindergarten teachers, 291 food industry workers, 48 musicians, 137 dental nurses, and 192 pharmacists: 855 mother-child pairs in total. Data on exposure and language acquisition were collected using several questionnaires, in two phases (Fig 1).

Phase 1. The Baseline questionnaire was sent at the same time to all the 855 women found from among the five trade union members. The children were then between 6 weeks and 11 months old. The questionnaire focused on background factors such as maternal employment,
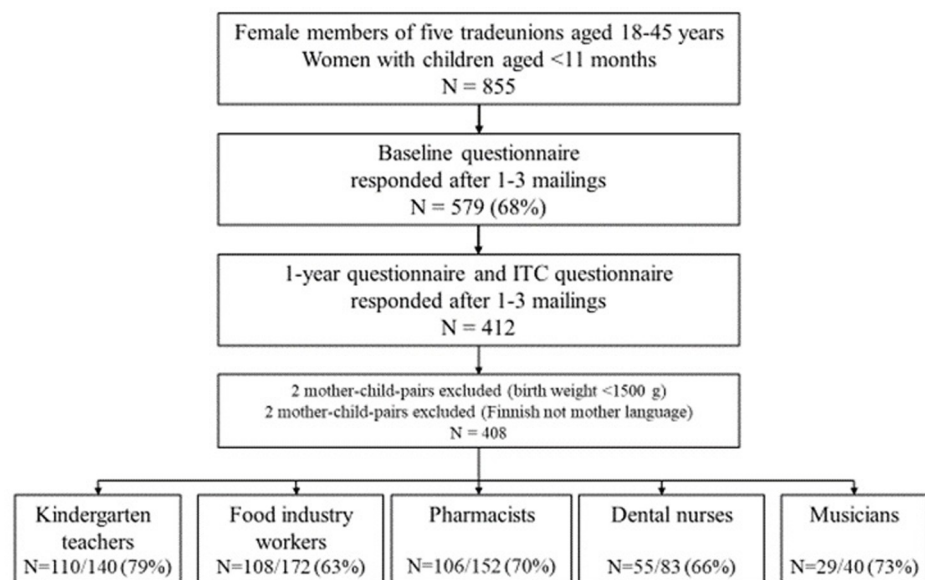

Fig 1. Flow chart of data collection and participation at baseline and when child was one (ITC = Infant-Toddler Checklist). Percentages in brackets (%) indicate proportion of women who returned questionnaire.

detailed work task descriptions, and exposure to occupational noise and stress during pregnancy. The questions on noise were a) "During your pregnancy, did the noise in your working environment disturb normal conversation?", b) "During your pregnany, was the noise in your work environment so loud that you could not hear normal speech from one meter's distance?". The weekly duration of such noise and the use of hearing protection devices were also elicited. These kinds of questions have been found to be practical for estimating noise level [24]. A study of construction workers by Neitzel [25] showed that trade was a poor predictor of noise exposure, whereas an internal validation study indicated good agreement between worker self-reporting and researcher observation. We also requested information on exposure to high-level leisure-time noise, its frequency (daily/weekly/more seldom) and the activity that caused it. Furthermore, we asked whether the women experienced stress (on a five-point Likert scale varying from 1 "not at all" to 5 "very much") during pregnancy and after birth. This question has shown to be valid for group-level analysis [26].

Phase 2a. The One-year background questionnaire included questions on the health (chronic diseases diagnosed by a physician before, during and after pregnancy as well as potential hearing problems) of the mother. It had detailed questions on the routine hearing tests (otoacoustic emission measurements) of the newborn child, ear infections, hospital treatments, malformations, and developmental disorders or other diseases or injuries during the child's first year of life. We also asked about possible day care, and the mothers' lifestyle factors (smoking or alcohol use). Communication between the mother and the child (frequency and duration of talking, reading and singing to the child, and the group activities of the child) was covered in detail in the questionnaire. Possible familiar first and second degree language acquisition disorders among relatives were elicited. We also asked about parental education (low = 9 years primary school; mid-level = high school or vocational school; high = university or university of applied sciences), and mother's exposure to ototoxic substances such as solvents, metals, or other chemicals.

Phase 2b. Data on the language acquisition of the child at the age of one were collected using the Finnish version of the Infant-Toddler Checklist (ITC) [27] called Esikko [28]. The ITC consists of 24 items (questions) organized into seven cluster areas that form three composites: social communication (expression of motions and eye gaze, communication, gestures), speech production (sounds, words) and language comprehension (language comprehension, object use). The maximum scores of the composites are: 26 for social communication, 14 for speech production, and 17 for language comprehension (57 in total). A higher score indicates a higher functioning. Total scores below 28 are typically referred to additional follow up consultations.

The Baseline questionnaire was sent to the 855 female trade union members three weeks to 11 months before their children turned one. Altogether 579 (68%) responded (Fig 1): 77% of the kindergarten teachers, 59% of the food industry workers, 79% of the dental nurses, 83% of the musicians, and 79% of the pharmacists. We sent the One-year background enquiry and ITC questionnaire (paper or web-based) to those who responded when their children turned one. Two reminders were sent if necessary. Altogether 412 (71% of baseline respondents and 48% of all the 855 women) women responded to both the One-year background questionnaire and the ITC questionnaire when their child was aged one year ± 1 weeks; 79% of the kindergarten teachers, 63% of the food industry workers, 66% of the dental nurses, 73% of the musicians, and 70% of the pharmacists. Children with a birth weight of <1500 g (N = 2) and women with a mother tongue other than Finnish (N = 2) were excluded. The final analyses consisted of 408 mother-child pairs.

Exposure assessment

An experienced occupational hygienist assessed the noise exposure of the women during pregnancy by combining existing information on noise exposure at Finnish workplaces in their professions and the questionnaire data. The range of exposure and workplace noise levels in the target professional groups are well known and documented. We used both published research data and results from The Finnish Database of Occupational Exposure Measurements (FDOEM) maintained by the Finnish Insitute of Occupational Health [29,30]. The questionnaires, in turn, elicited information on how the respondents were exposed to noise during pregnancy. The duration (no noise, noise <2 hours, 2–6 hours, 6–10 hours, >10 hours per week) of noisy events that disturbed or blocked speech communication (impossible to hear speech from a distance of one meter), type of identified noise sources at work, and the respondents' use of hearing protection were also used to help place each individual in the most plausible category within each occupational group. Noisy activities during leisure time were queried and classified separately. Exposure assessment was made blindly, without knowledge of the language acquisition of the child.

Exposure assessment among kindergarten teachers was based on two sets of data. In a FIOH research project in 25 randomly selected kindergartens, the range of daily noise exposure levels was 71–84 dB, and only in two of the 50 individual measurements did the level exceed 80 dB [29]. Thus, the majority of the kindergarten teachers was classified into the low-exposure category. However, in kindergartens in which the personnel reported disturbing noise and measurements were conducted (FDOEM), 67% of personal noise exposure measurements exceeded 80 dB. Therefore, teachers reporting weekly exposure to noise events that hindered communication were placed into the moderate exposure class.

Food industry work environments ranged from bakeries to food factories. The questionnaire asked about the individual type of work (bakery, meat processing, food service, packing, box washing line) and produced items. In previous measurements, exposure had ranged from low to >85 dB (FDOEM).

In dental care, noise producing equipment are: high-/slow-speed hand pieces, suction tubes, ultrasonic scalers, and compressed air. The exposure assessment was based on self-reported tool usage, and noise levels were reported elsewhere. In Finland, typical dental tool noise level has been measured as 78–83 dB, but internationally higher noise levels have also been reported [31,32].

We asked the musicians about their main and side instrument as well as singing, the size of their orchestra or group, type of music (classical, rock, chorus), and the weekly time of rehearsal, performances, and possible teaching lessons. Several projects have assessed musicians' noise exposure in Finnish professional orchestras and musical education. The sound level for symphony orchestra musicians is 83–96 dB, depending on instrument and position [30]. The majority of the musicians in our data were classical orchestra musicians. The others were either full-time or semi-professional performers of popular music genres. The sound level of amplified music during practice and performance was assumed to exceed 90 dB on the basis of measurements during concerts, in which levels of 95–105 dB have been registered (FDOEM).

Based on the questionnaires, the pharmacists were assessed as non-exposed. Occasional repair work nearby, for example, could cause low exposure.

Occupational noise exposure (the highest exposure level in any pregnancy trimester) was classified into one of the four categories:

1. Non-exposed: Environmental sounds come mostly from speaking, normal office equipment or home sounds.

2. Low exposure: The presence of environmental noise becomes noticeable and requires the use of a raised voice during conversation. Noise sources in these environments can be, for example, groups of people talking loudly, or quiet machinery or brief occurences of higher level sounds. The approximate range of noise exposure level in this category is 70–78 dB.

3. Moderate exposure: Noise and loud sounds make conversation difficult but do not block it. The approximate range of daily noise exposure level is 79–84 dB. Many of these workers consider hearing protection useful.

4. High exposure: The sound or noise level is so high that conversation is difficult or blocked most of the working time, and the risk of hearing loss is high. Typical noise exposure is >85 dB, and the use of hearing protection is mandatory.

Statistical analyses

We compared the language acquisition of children of mothers exposed to noise at work during pregnancy to the language acquistion of children of non-exposed working mothers. As a measure of language acquisition, we used the summary score of the ITC questionnaire and the scores of its three composites: social communication, speech production and language comprehension.

We used multivariable linear regression to assess the mean differences between the language acquisition scores in the occupational exposure categories. Statistical significance was determined by 95% confidence intervals (CI). Missing ITC score data were replaced by the mean values of each occupational group (one dental nurse and one pharmacist) in the single items. The analyses were performed using SAS 9.4® and IBM SPSS Statistics 23®.

Due to the small number of women in the highest category, the two highest noise exposure categories, moderate and high, were combined for statistical analyses. The exposed and non-exposed women in the four occupational groups were also analyzed separately, but not the musicians, because of their small number. Women who were not working during pregnancy (N = 54) or did not work in the occupation corresponding to their trade union (9 dental nurses and 3 food industry workers) were excluded from these analyses. One musician and one dental nurse who worked in a kindergarten were transferred to the kindergarten teacher group.

On the basis of earlier studies, we identified a number of potential confounders on factors which may affect a child's language acquisition. The factors that were associated with language acquisition in our data, and which were included in the final multivariable models as potential confounders were maternal age (20–34 and 35–44 years), talking (<1 hour/day, ≥1 hour/day), looking at and reading books (not yet or occasionally, a few times a week, daily) and singing to the child (never or occasionally, a few times a week, daily). The boys and girls were analyzed separately, as their language acquisition scores clearly differed. However, we adjusted for gender in the analyses by occupational group. Other potential confounding factors, such as parental education, mother's use of alcohol, diabetes mellitus during pregnancy, history of acute otitis media, number of siblings, or language disorders among close relatives were not associated with the child's language acquisition and were therefore not included in the final models.

The following health conditions were very rare in our data (<5% of the observations) and were not included in the final models: preterm birth, low birth weight, low APGAR score, congenital abnormalities or postnatal diseases requiring hospital treatment, child's hearing loss, abnormal results in otoacoustic emission measurements as newborn (3 children), and mother's chronic diseases (mental disorders, hyperthyreosis or hypothyreosis, diabetes mellitus, or other serious illness diagnosed by a physician), maternal hepatogestosis, and smoking. The same applies to noise exposure during leisure time, because it was not associated with language

acquisition. Most children were taken care of at home (92.4%); only 7.6% (N = 31) outside the home. Thus, for the majority, the noise was at normal family-life level.

Ethics approval

The research plan was approved by the Coordinating Ethical Committee of the Hospital District of Helsinki and Uusimaa (approval number 54/13/03/00/13).

Results

About 87% (N = 354) of the mothers worked during their pregnancy. About 36% of these mothers were not exposed to occupational noise, 31% were exposed to low levels of noise, 21% to moderate noise, and 12% to high-level noise. Only the musicians and food industry workers were exposed to high-level noise.

The group of children of highly exposed mothers included more girls (66%) than boys (34%), whereas the sex ratio in other groups was even. Table 1 shows further background characteristics by levels of noise exposure.

Time spent talking to their children was shorter among the non-exposed mothers than among the other mothers (Table 2). 46% read daily to their children. There were no systematic differences in terms of looking at and reading books between the exposure categories. The moderately or highly exposed mothers sang more often to their children than the mothers in other groups. There were no clear differences in terms of attending musical play school or other activities between the exposure groups.

There were no statistically significant differences between the language acquisition total scores of the boys or girls according to maternal exposure categories (Table 3). The girls achieved significantly higher language acquisition mean scores (35.8) than the boys (33.3) ($P<0.001$). Among the boys, the adjusted mean differences in ITC scores were -0.4 (95% CI -2.5, 1.8) for low exposure, and -0.7 (95% CI -2.9, 1.4) for moderate/high exposure, in comparison to the non-exposed. Among the girls these were +0.1 (95% CI -2.2, 2.5) and -0.1 (95% CI -2.3, 2.2), respectively (Table 3). Among the boys, reading and speaking to one's child was associated with high language acquisition scores, as well as maternal age at birth (<35 years) and working status during pregnancy. Among the girls, only reading was related to high scores.

No clear associations were found between noise exposure and the different composites of language acquisition including child's social communication, speech production and language comprehension (Table 4).

Analyses by occupational group were restricted to the mothers who worked during pregnancy (N = 354) (Table 5). Compared to no exposure, low or moderate noise exposure was associated with lower language acquisition scores among the children of kindergarten teachers, and with language comprehension in particular. The adjusted mean score of this composite was 9.2 (mean difference -1.3 (95% CI -2.5, -0.1, $P<0.05$)) for low exposure and 9.1 (mean difference -1.5, 95% CI -2.8, -0.2, $P<0.05$) for moderate exposure. The mean score for the non-exposed was 10.5 in comparison.

To test whether these associations could be explained by stress, as a sensitivity analysis we included maternal stress during pregnancy in the models. The results were virtually unchanged in terms of the total and composite scores. No associations between noise exposure and language acquisition were seen among the food industry workers. The children of the musicians had a relatively high mean total score (35.6). Due to small numbers, it was not possible to analyze their language acquisition by noise level.

Table 1. Characteristics of study participants by estimated occupational noise exposure during pregnancy.

Characteristics	Occupational noise exposure			
	No exposure	Low exposure	Moderate exposure	High exposure
	N (%)	N (%)	N (%)	N (%)
Occupational group				
Kindergarten teachers	15 (8)	52 (48)	28 (37)	0 (0)
Musicians	2 (1)	3 (3)	7 (9)	16 (36)
Food industry workers	14 (8)	19 (8)	25 (33)	28 (64)
Dental nurses	13 (7)	20 (19)	16 (21)	0 (0)
Pharmacists	82 (46)	14 (13)	0 (0)	0 (0)
Unemployed	54 (30)	-	-	-
Total	180	108	76	44
Child's mother				
Maternal age at birth (years)				
$\leq$35	147 (82)	93 (86)	64 (84)	37 (84)
>35	33 (18)	15 (14)	12 (16)	7 (16)
Maternal education				
Low	1 (1)	0 (0)	3 (4)	3 (7)
Mid-level	45 (25)	26 (24)	31 (41)	23 (52)
High	134 (74)	81 (75)	41 (54)	18 (41)
Unknown	0 (0)	1 (1)	1 (1)	0 (0)
Smoking during pregnancy				
Yes	6 (3)	6 (6)	3 (4)	6 (14)
No	174 (97)	101 (94)	72 (95)	38 (86)
Unknown	0 (0)	1 (1)	1 (1)	0 (0)
Alcohol use during pregnancy				
Yes	14 (8)	7 (7)	5 (7)	3 (7)
No	166 (92)	101 (94)	71 (93)	41 (93)
Stress during pregnancy				
Not at all	22 (12)	17 (16)	10 (13)	4 (9)
Only a little	78 (43)	41 (38)	34 (45)	22 (50)
Some	62 (34)	38 (35)	25 (33)	11 (25)
Rather much/very much	18 (10)	12 (11)	7 (9)	7 (16)
Child's father				
Paternal education				
Low	4 (2)	3 (3)	5 (7)	1 (2)
Mid-level	87 (48)	58 (54)	33 (43)	25 (57)
High	86 (48)	45 (42)	36 (47)	17 (39)
Unknown	3 (2)	2 (2)	2 (3)	1 (2)
Child				
Gender				
Female	87 (48)	54 (50)	38 (50)	29 (66)
Male	93 (52)	54 (50)	38 (50)	15 (34)
Gestational age (weeks)				
$\geq$37	178 (99)	102 (94)	69 (91)	40 (91)
<37	1 (1)	4 (4)	3 (4)	3 (7)
Unknown	1 (1)	2 (2)	4 (5)	1 (2)
Birth weight (grams)				

(Continued)

Table 1. (Continued)

Characteristics	Occupational noise exposure			
	No exposure	Low exposure	Moderate exposure	High exposure
	N (%)	N (%)	N (%)	N (%)
<2500	1 (1)	2 (2)	2 (3)	1 (2)
<4500 but ≥2500	174 (97)	101 (94)	66 (87)	42 (96)
≥4500	5 (3)	4 (4)	8 (11)	1 (2)
Unknown	0 (0)	1 (1)	0 (0)	0 (0)
Acute otitis media				
0–2	164 (91)	104 (96)	70 (92)	41 (93)
≥3	15 (8)	4 (4)	5 (7)	3 (7)
Unknown	1 (1)	0 (0)	1 (1)	0 (0)
Congenital abnormalities				
No	175 (93)	105 (97)	72 (95)	44 (100)
Yes	5 (3)	3 (3)	4 (5)	0 (0)
Language disorders in close relatives				
No	167 (93)	97 (90)	70 (92)	39 (89)
Yes	10 (6)	10 (9)	5 (7)	5 (11)
Unknown	3 (2)	1 (1)	1 (1)	0 (0)
Siblings				
0	66 (37)	45 (42)	39 (51)	25 (57)
1	70 (39)	38 (35)	23 (30)	13 (30)
>2	44 (24)	25 (23)	14 (18)	6 (14)
Child at day care				
No	169 (94)	98 (91)	67 (88)	41 (93)
Yes	9 (5)	10 (9)	9 (12)	3 (7)
Unknown	2 (1)	0 (0)	0 (0)	0 (0)

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Discussion

Principal findings

We found no clear association between maternal occupational noise exposure to low exposure (approximately 70–78 dB) or moderate and high exposure (approximately >79 dB) and the child's language acquisition at one year of age in the entire data. The results were similar when we studied the three different composites of language acquisition: social communication, speech production and language comprehension. Accordingly, industrial noise among food industry workers or noise in dental clinics showed no association with children's language acquisition.

No previous studies have examined the effects of prenatal occupational noise exposure on the language acquisition of children at one year of age. Earlier studies have focused on prenatal noise exposure effects on hearing impairments among children [20–23], and the findings of these studies have been conflicting. Some studies have associated maternal exposure to high noise levels (>85 dB) with hearing deterioration among children, whereas others have indicated no hearing impairment after exposure.

Among the children of the kindergarten teachers, who were mainly exposed to human noise, low or moderate noise exposure was associated with lower language acquisition scores. In addition to noise, stress during pregnancy might be a potential risk factor for lower language acquisition. Laplante [33] observed that stress during pregnancy affects the language

Table 2. Communication between mother and child and child's activities by estimated occupational noise exposure during pregnancy.

Communication and activities	Occupational noise exposure			
	No exposure	Low exposure	Moderate exposure	High exposure
	N (%)	N (%)	N (%)	N (%)
Talking to child				
Daily, <1 hour	39 (22)	13 (12)	5 (7)	6 (14)
Daily, ≥1 hour	140 (78)	94 (87)	71 (93)	38 (86)
Unknown	1 (1)	1 (1)	0 (0)	0 (0)
Looking at or reading books to child				
Not yet or occasionally	49 (27)	21 (19)	12 (16)	15 (34)
A few times a week	54 (30)	29 (27)	33 (43)	6 (14)
Daily	77 (43)	55 (51)	31 (41)	23 (52)
Unknown	0 (0)	3 (3)	0 (0)	0 (0)
Singing to child				
Never or occasionally	16 (9)	14 (13)	8 (11)	2 (5)
A few times a week	38 (21)	26 (24)	10 (13)	8 (18)
Daily	124 (69)	68 (63)	58 (76)	34 (77)
Unknown	2 (1)	0 (0)	0 (0)	0 (0)
Child attends musical playschool				
Yes	49 (27)	25 (23)	20 (26)	12 (27)
No	131 (73)	83 (77)	56 (74)	32 (73)
Child participates in activities other than musical playschool				
Yes	56 (31)	30 (28)	19 (25)	14 (32)
No	124 (69)	78 (72)	57 (75)	30 (68)
Child participates in both musical playschool and other activities				
Yes	25 (14)	8 (7)	8 (11)	7 (16)
No	155 (86)	100 (93)	68 (90)	37 (84)

functioning of human toddlers. Stress could be either a confounding factor or an intermediate variable in the causal pathway from noise exposure to language acquisition. However, our analyses indicated no role for stress because the association of noise with children's language acquisition was virtually unchanged after adjustment for maternal stress during pregnancy.

Most of the musicians were exposed to moderate or high noise levels, but the ITC scores for their children were relatively high. Earlier studies [34] have shown music to have positive effects on language acquisition. Accordingly, a number of studies have revealed that children who undergo music training have stronger cognitive linguistic abilities, for example in vocabulary and perception, than children with no musical training [16].

Noise exposure in different trimesters may have different effects in the child's later development, but studies of the effects of noise on the human fetus during different stages of pregnancy are lacking. Some studies of pregnant animals have shown noise exposure to have adverse effects on fetal hearing during late pregnancy [35,36]. There is, however, a possibility of that noise can have an adverse effect on hearing even during the embryonic period in the first trimester, when the auditory system is developing. The otocyst embryonic stem cells can produce hair cell-like cells [37], and these cells may react to loud sounds. According to these studies, it is not possible to indicate the stage of pregnancy when noise could harm the fetus [23]. We used the highest estimate in any pregnancy trimester as the exposure estimate.

Table 3. Crude and adjusted mean differences between ITC total language acquisition scores of one-year-old boys and girls by estimated noise exposure during pregnancy. Adjusted for mother's age at birth; working status during pregnancy; and talking, reading and singing to one's child. A multivariable model.

Variable	N	Mean score	Crude	Adjusted	95% CI	P value	N	Mean score	Crude	Adjusted	95% CI	P value
			Boys						Girls			
			Mean differences between ITC scores						Mean differences between ITC scores			
Occupational noise exposure												
No exposure	68	32.6				Reference	58	35.6				Reference
Low exposure	54	33.7	+1,1	-0.4	-2.5, 1.8	0.724	54	36.0	+0.4	+0.1	-2.2, 2.5	0.912
Moderate/high exposure	53	34.0	+1.4	-0.7	-2.9, 1.4	0.498	67	35.8	+0.2	-0.1	-2.3, 2.2	0.962
Mother's working status during pregnancy												
No	25	30.6				Reference	29	34.8				Reference
Yes	175	33.7	+3.1	+2.9	0.2, 5.6	0.035	179	35.9	+1.1	+0.7	-2.2, 3.6	0.631
Maternal age at birth												
≥35	41	31.0				Reference	47	35.9				Reference
<35	159	33.9	+2.9	+2.9	0.9, 4.9	0.005	161	35.7	-0.2	-0.2	-2.3, 1.9	0.861
Reading to child												
Occasionally	53	30.0				Reference	44	32.9				Reference
A few times a week	59	34.0	+4.0	+3.6	1.4, 5.9	0.002	66	34.9	+2.0	+1.5	-1.0, 4.0	0.239
Daily	88	34.8	+4.8	+3.8	1.6, 6.0	0.001	98	37.6	+4.7	+3.6	1.1, 6.0	0.004
Singing to child												
Occasionally	17	30.6				Reference	23	32.7				Reference
A few times a week	41	33.3	+2.7	+1.3	-2.1, 4.7	0.460	43	34.0	+1.3	+0.5	-2.8, 3.9	0.745
Daily	142	33.6	+3.0	+1.1	-2.0, 4.3	0.478	142	36.8	+4.1	+2.6	-0.4, 5.6	0.087
Talking to child												
Daily, <1 hour	31	29.7				Reference	32	33.5				Reference
Daily, ≥1 hour	169	33.9	+4.2	+3.0	0.6, 5.4	0.015	176	36.2	+2.7	+1.5	-1.0, 4.0	0.231

Strengths of the study

The main strengths of our study were the use of a validated measure of language acquisition and careful, blinded assessment of exposure to noise by an experienced occupational hygiene engineer. Expert assessment, based on both questionnaires and measurements, has been considered the best approach among exposure estimation methods [38]. Our assessment relied on information regarding earlier industrial hygiene measurements in the same or similar workplaces, women's detailed descriptions of their working tasks, the level and duration of workplace noise exposure, and the women's experience of disturbing noise. Self-reported data on occupational noise exposure is suggested to be a valid source when assessing exposure [39]. The background information on noise exposure and specific work tasks during pregnancy was collected several months before the mother filled out the ITC questionnaires on language acquisition. We therefore consider it unlikely that recall bias affected the reported noise exposure during pregnancy.

The ITC is designed for screening purposes, but it has also been used in research on language acquisition [40–42]. It has shown to be able to detect developmental growth and produce relatively stable rankings of children over short periods of time [43,44]. Määttä [42] also indicated that the individual differences in the development of prelinguistic skills showed rather high stability throughout the prelinguistic period. This suggests that even one measurement may give

Table 4. Crude and adjusted mean differences between ITC scores in three composites of language acquisition of one-year-old boys and girls by estimated noise exposure during pregnancy. Adjusted for mother's age at birth; working status during pregnancy; and talking, reading and singing to one's child.

Composites of language acquisition by noise exposure	Boys					Girls				
	Mean score	Mean differences between ITC scores				Mean score	Mean differences between ITC scores			
		Crude	Adjusted	95% CI	P value		Crude	Adjusted	95% CI	P value
Social communication										
No exposure	17.8				Reference	18.9				Reference
Low exposure	18.1	+0.3	-0.5	-1.7, 0.7	0.376	19.2	+0.3	-0.1	-1.4, 1.1	0.814
Moderate/high exposure	18.4	+0.6	-0.4	-1.6, 0.8	0.513	19.2	+0.3	-0.03	-1.2, 1.1	0.961
Speech production										
No exposure	5.8				Reference	6.9				Reference
Low exposure	6.4	+0.6	+0.2	-0.6, 1.1	0.615	7.4	+0.5	+0.7	-0.2, 1.6	0.139
Moderate/high exposure	6.6	+0.8	+0.1	-0.7, 1.0	0.778	6.8	-0.1	-0.003	-0.9, 0.9	0.995
Language comprehension										
No exposure	9.0				Reference	9.8				Reference
Low exposure	9.2	+0.2	-0.1	-0.8, 0.7	0.868	9.4	-0.4	-0.4	-1.3, 0.5	0.372
Moderate/high exposure	8.9	-0.1	-0.5	-1.2, 0.3	0.205	9.7	-0.1	-0.02	-0.9, 0.8	0.956

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Table 5. Adjusted mean differences between ITC total scores of one-year-old children of employed mothers by estimated noise exposure and mother's occupation during pregnancy. [1]Adjusted for gender of child. [2]Adjusted for gender of child; mother's age at birth; and talking, reading and singing to one's child. ITC total score range 0–57.

Noise exposure by occupational group	N	ITC score	Mean differences between ITC scores			ITC score	Mean differences between ITC scores		
		Adjusted[1] mean	Adjusted[1]	95% CI	P value	Adjusted[2] mean	Adjusted[2]	95% CI	P value
Kindergarten teachers									
No exposure	15	39.5	Reference			37.3	Reference		
Low exposure	53	35.8	-3.7	-7.0, -0.4	0.030	33.5	-3.8	-7.2, -0.4	0.030
Moderate exposure	29	34.8	-4.7	-8.3, -1.1	0.012	32.4	-4.9	-8.6, -1.2	0.010
Food industry workers									
No exposure	12	32.9	Reference			31.3	Reference		
Low exposure	19	33.9	+1.0	-3.8, +5.7	0.689	32.6	+1.3	-3.6, +6.2	0.593
Moderate/high exposure	52	34.1	+1.2	-2.9, +5.3	0.561	32.8	+1.5	-2.8, +5.8	0.482
Dental nurses									
No exposure	8	38.8	Reference			36.7	Reference		
Low exposure	15	33.6	-5.1	-10.2, -0.01	0.050	33.6	-3.1	-8.1, +1.8	0.205
Moderate exposure	16	35.5	-3.2	-8.3, +1.9	0.205	34.0	-2.7	-7.4, +2.1	0.264
Pharmacists									
No exposure	82	33.6	Reference			31.3	Reference		
Low exposure	14	33.3	-0.4	-4.0, +3.3	0.847	31.1	-0.2	-3.8, +3.4	0.903

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relatively permanent data on a child's linguistic skills. Moreover, parent-report measures of communication and language skills have shown to be reliable and valid [45,46].

We considered several known determinants of language acquisition in the statistical analyses. In line with the literature, the older age of the mother and the child's male gender were associated with lower language acquisition scores in our study, which indicates its validity [20]. Speaking, reading and singing to one's child, in turn, were associated with high language acquisition scores in our data, which is also in line with earlier results [47].

This study focused on branches of work in which women are exposed to noise and obtained the data on these women from trade union registers. The women's detailed descriptions of their work during pregnancy tasks made it possible to classify them accurately by occupation for the analyses. Thus, the information on occupation was reliable. The response rate was fairly good at baseline and when the children were 12 months old.

Limitations of the study

However, our study has some limitations. Firstly, the number of mothers exposed to occupational noise of ≥85 dB was small, precluding analyses of higher exposure levels. Secondly, we could not separately analyze exposure to low frequency noise due to a lack of frequency-specific exposure data. Thirdly, we were not able to measure individual noise exposure. Thus, some misclassification of exposure may have occurred despite the exposure being assessed by an experienced occupational hygiene engineer, who used several data sources. In addition, the frequency of women in the highest exposure group declined in the last weeks of pregnancy (after 29 pregnancy weeks). If the most critical period is the last trimester with regard to language development, this could have introduced some misclassification of exposure. However, noise exposure was undoubtedly higher in the moderate/high exposure category than in the no-exposure group. Fourthly, we cannot totally rule out the fact that selective participation may have caused bias in the results. Furthermore, there is a possibility that our assessment measures did not reveal minor difficulties in language acquisition. Finally, at the age of one, language acquisition among children may vary considerably. For these reasons, the results regarding the effect of noise exposure on language acquisition are only suggestive.

Conclusions

This is the first study to investigate the potential association between maternal noise exposure and children's language acquisition. In general, our findings suggest no association between occupational noise exposure during pregnancy and language acquisition among one-year-old children. The children of kindergarten teachers exposed to human noise had lower language acquisition scores than the children of the non-exposed teachers, but this result should be interpreted with caution. Our suggestive findings warrant future studies by level and type of exposure.

Supporting information

S1 Checklist. *PLOS ONE* clinical studies checklist.
(DOCX)

S2 Checklist. STROBE statement—checklist of items that should be included in reports of observational studies.
(DOCX)

S1 File.
(PDF)

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References

1. Gerhardt KJ, Abrams RM, Huang X, Griffiths SK, Peters AJ. Intra-abdominal sound pressure levels during impulse noise exposure in sheep. Mil Med 2000; 165:153–156. PMID: 10709379

2. Gerhardt KJ, Abrams RM. Fetal exposures to sound and vibroacoustic stimulation. J Perinat 2000; 20:20–9. https://doi.org/10.1038/sj.jp.7200446 PMID: 11190697

3. Huotilainen M, Kujala A, Hotakainen M, Shestakova A, Kushnerenko E, Parkkonen L, et al. Auditory magnetic responses of healthy newborns. Neuroreport 2003; 14:1871–5. https://doi.org/10.1097/00001756-200310060-00023 PMID: 14534438

4. Kim CH, Lee SC, Shin JW, Chung KJ, Lee SH, Sin MS, et al. Exposure to music and noise during pregnancy influences neurogenesis and thickness in motor and somatosensory cortex of rat pups. Int Neurourol J 2013; 17:107–13. https://doi.org/10.5213/inj.2013.17.3.107 PMID: 24143288

5. Kim H, Lee MH, Chang HK, Lee TH, Lee HH, Shin MC, et al. Influence of prenatal noise and music on the spatial memory and neurogenesis in the hippocampus of developing rats. Brain Dev 2006; 28:109–14. https://doi.org/10.1016/j.braindev.2005.05.008 PMID: 16181757

6. Huotilainen M. Building blocks of fetal cognition: emotion and language. Infant Child Dev 2010;19. 1:94–8.

7. Partanen E, Kujala T, Näätänen R, Liitola A, Sambeth A, Huotilainen M. Learning-induced neural plasticity of speech processing before birth. Proceedings of the National Academy of Sciences USA 2013[b]; 110:15145–50. https://doi.org/10.1073/pnas.1302159110 PMID: 23980148

8. Rand K, Lahav A. Impact of the NICU environment on language deprivation in preterm infants. Acta Paediatr 2014; 103:243–8. https://doi.org/10.1111/apa.12481 PMID: 24164604

9. Kujala T, Brattico E. Detrimental noise effects on brain's speech functions. Biol Psychol 2009; 81:135–43. https://doi.org/10.1016/j.biopsycho.2009.03.010 PMID: 19482230

10. Niemitalo-Haapola E, Haapala S, Kujala T, Raappana A, Kujala T, Jansson-Verkasalo E. Noise equally degrades central auditory processing in 2- and 4-year-old children. J Speech Lang Hear Res 2017; 60:2297–309. https://doi.org/10.1044/2017_JSLHR-H-16-0267 PMID: 28763806

11. Jansson-Verkasalo E, Ruusuvirta T, Huotilainen M, Alku P, Kushnerenko E, Suominen K, et al. Atypical perceptual narrowing in prematurely born infants is associated with compromised language acquisition at 2 years of age. BMC Neurosci 2010; 11:88. https://doi.org/10.1186/1471-2202-11-88 PMID: 20673357

12. Kuhl PK, Conboy BT, Coffey-Corina S, Padden D, Rivera-Gaxiola M, Nelson T. Phonetic learning as a pathway to language: New data and native language magnet theory expanded (NLM-e). Philosophical transactions of the Royal Society of London. Series B, Biological sciences Royal Society (Great Britain) 2008; 363:979–1000. https://doi.org/10.1098/rstb.2007.2154 PMID: 17846016

13. Kraus N, Hornickel J, Strait DL, Slater J, Thompson E. Engagement in community music classes sparks neuroplasticity and language development in children from disadvantaged backgrounds. Front Psychol 2014; 16:1–9. https://doi.org/10.3389/fpsyg.2014.01403 PMID: 25566109

14. Paavola L, Kemppinen K, Kumpulainen K, Moilanen I, Ebeling H. Maternal sensitivity, infant co-operation and early linguistic development: Some predictive relations. Eur J Dev Psychol 2006; 3:13–30.

15. Pineda R, Guth R, Herring A, Reynolds I, Oberle S, Smith J. Enhancing sensory experiences for very preterm infants in the NICU: an integrative review. J Perinatol 2017; 37:323–32. https://doi.org/10.1038/jp.2016.179 PMID: 27763631

16. Schön D, Boyer M, Moreno S, Besson M, Peretz I, Kolinsky R. Songs as an aid for language acquisition. Cognition 2008; 106:975–83. https://doi.org/10.1016/j.cognition.2007.03.005 PMID: 17475231

17. Webb AR, Heller HT, Benson CB, Lahav A. Mother's voice and heartbeat sounds elicit auditory plasticity in the human brain before full gestation. Proceedings of the National Academy of Sciences USA 2015; 112:3152–7. https://doi.org/10.1073/pnas.1414924112 PMID: 25713382

18. Shi LF. Perception of acoustically degraded sentences in bilingual listeners who differ in age of English acquisition. J Speech Lang Hear Res 2010; 53:821–35. https://doi.org/10.1044/1092-4388(2010/09-0081) PMID: 20220026

19. Korpilahti P, Kaljonen A, Jansson-Verkasalo E. Population-Based Screening for Language Delay: Let's Talk STEPS Study. Psych 2016; 7:215–4.

20. Daniel T, Laciak J. Clinical observations and experiments concerning the condition of the cochleovestibular apparatus of subjects exposed to noise in fetal life. Rev Laryngol Otol Rhinol (Bord) 1982; 103:313–8. French.

21. Lalande NM, Hétu R, Lambert J. Is occupational noise exposure during pregnancy a risk factor of damage to the auditory system of the fetus? Am J Ind Med 1986; 10:427–35. https://doi.org/10.1002/ajim.4700100410 PMID: 3788986

22. Rocha EB, Frasson de Azevedo M, Ximenes Filho JA. Study of the hearing in children born from pregnant women exposed to occupational noise: Assessment by distortion product otoacoustic emissions. Braz J Otorhinolaryngol 2007; 73:359–69. https://doi.org/10.1016/s1808-8694(15)30080-x PMID: 17684657

23. Selander J, Albin M, Rosenhall U, Rylander L, Lewné M, Gustavsson P. Maternal occupational exposure to noise during pregnancy and hearing dysfunction in children: A Nationwide Prospective Cohort Study. Environ Health Perspect 2016; 124:855–60.

24. Kauppinen T, Hanhela R, Kandolin I, Karjalainen A, Kasvio A, Perkiö-Mäkelä M, et al. Editors. Work and Health in Finland 2009 (Työ ja terveys Suomessa 2009). The Finnish Institute of Occupational Health 2009. ISBN 978-951-802-943-7, ISBN 978-802-952-9 (PDF). Vammalan Kirjapaino Oy, Sastamala 2010. Finnish.

25. Neitzel R, Seixas NS, Camp J, Yost M. An assessment of occupational noise exposures in four construction trades. Am Ind Hyg Assoc J 1999; 60:807–17. https://doi.org/10.1080/00028899908984506 PMID: 10635548

26. Elo AL, Leppänen A, Jahkola A. Validity of a single-item measure of stress symptoms. Scand J Work Environ Health 2003; 29:444–51. https://doi.org/10.5271/sjweh.752 PMID: 14712852

27. Wetherby AM, Prizant BM. Communication and Symbolic Behavior Scales Developmental Profile. Infant/Toddler Checklist. Paul H. Brookes Publishing Co. 2001.

28. Laakso ML, Eklund K, Poikkeus AM. Infant Toddler Checklist (ITC) for Finnish Language. (Esikko. Lapsen esikielellisen kommunikaation ja kielen ensikartoitus). Niilo Mäki Instituutti 2010. ISBN: 978-951-39-4128-4. Finnish.

29. Sala E, Airo E, Olkinuora P, Simberg S, Ström U, Laine A, et al. J. Vocal loading among day care center teachers. Logoped Phoniatr Vocol 2002; 27:21–8.

30. Toppila E, Starck J, Koskinen H, Pyykkö I. Classical music and hearing protection. (Klassinen musiikki ja kuulonsuojelu). Työympäristötutkimuksen raporttisarja 10. Finnish Institute of Occupational Health 2004. ISBN 951-802-591-6, ISSN 1458-9311. Finnish.

31. Rytkönen E. High Frequency Vibration and Noise in Dentistry. Doctoral dissertation. Department of Environmental Sciences. University of Kuopio 2005. ISBN 951-781-318-X.

32. Dutta A, Mala K, Acharya SR. Sound levels in conservative dentistry and endodontic clinics. J Conserv Dent 2013; 16:121–5.

33. Laplante DP, Barr RG, Brunet A, Galbaud duFort G, Meaney ML, Saucier JF, et al. Stress during pregnancy affects general intellectual and language functioning in human toddlers. Ped Res 2004; 56:400–10. https://doi.org/10.1203/01.PDR.0000136281.34035.44 PMID: 15240860

34. Patel AD. Music, language, and the brain. Oxford University Press 2007. ISBN-13: 9780195123753. DOI: 10.1093/acprof:oso/9780195123753.001.0001.

35. Cook RO, Konishi T, Salt AN, Hamm CW, Lebetkin EH, Koo J. Brainstem-evoked responses of guinea pigs exposed to high noise levels in utero. Dev Psychobiol 1982; 15:95–104. https://doi.org/10.1002/dev.420150202 PMID: 7095284

36. Gerhardt KJ, Pierson LL, Huang X, Abrams RM, Rarey KE. Effects of intense noise exposure on fetal sheep auditory brain stem response and inner ear histology. Ear Hear 1999; 20:21–32. https://doi.org/10.1097/00003446-199902000-00003 PMID: 10037063

37. Woods C, Montcouquiol M, Kelley MW. Math1 regulates development of the sensory epithelium in the mammalian cochlea. Nat Neurosci 2004; 12:1310–8. https://doi.org/10.1038/nn1349 PMID: 15543141

38. Teschke K, Olshan AF, Daniels JL, De Roos AJ, Parks CG, Schulz M, et al. Occupational exposure assessment in case-control studies: opportunities for improvement. Occup Environ Med 2002; 59:575–93; discussion 594. Review. https://doi.org/10.1136/oem.59.9.575 PMID: 12205230

39. Schlaefer K, Schlehofer B, Schüz J. Validity of self-reported occupational noise exposure. Eur J Epidemiol 2009; 24:469–75. https://doi.org/10.1007/s10654-009-9357-4 PMID: 19543796

40. Määttä S, Laakso ML, Tolvanen A, Ahonen T, Aro T. Developmental trajectories on early communication skills. J Speech Lang Hear Res 2012; 44:873–85.

41. Määttä S, Laakso ML, Tolvanen A, Ahonen T, Aro T. Children With Differing Developmental Trajctories of preliguistic Communication Skills: Language and Working Memory at Age 5. J Speech Lang Hear Res 2014; 57:1026–39.

42. Määttä S, Laakso ML, Ahonen T, Tolvanen A, Westerholm J, Aro T. Continuity from Prelinguistic Communication to Later Language Ability: A Follow-Up Study From Infancy to Early School Age. J Speech Lang Hear Res 2016; 59:1357–72. https://doi.org/10.1044/2016_JSLHR-L-15-0209 PMID: 27788278

43. Reilly S, Eadie P, Bavin EL, Wake M, Prior M, Williams J, et al. Growth of infant communication between 8 and 12 months: a population study. J Paed Child Health 2006; 42:764–70. https://doi.org/10.1111/j.1440-1754.2006.00974.x PMID: 17096710

44. Wetherby AM, Allen L, Cleary J, Kublin K, Goldstein H. Validity and reliability of the communication and symbolic behavior scales developmental profile with very young children. J Speech Lang Hear Res 2002; 45:1202–18. https://doi.org/10.1044/1092-4388(2002/097) PMID: 12546488

45. Feldman HM, Dale PS, Campbell TF, Colborn DK, Kurs-Lasky M, Rockette HE, Paradise JL, et al. Concurrent and predictive validity of parent reports of child language at ages 2 and 3 years. Child Dev 2005; 76:856–68. https://doi.org/10.1111/j.1467-8624.2005.00882.x PMID: 16026501

46. Laakso ML, Poikkeus J, Katajamäki J, Lyytinen P. Early intentional communication as a predictor of language development in young toddlers. First Lang 1999; 19:207–31.

47. Kalb G, van Ours J. Reading to Young Children: A Head-Start in Life? Econ Educ Rev 2014; 40:1–24.