Occupant satisfaction with indoor environmental quality and health after energy retrofits of multi-family buildings: results from INSULAtE-project

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Running title: Energy retrofits, IEQ, and occupant health perceptions

Abstract

Background: Driven by climate change mitigation, EU countries are committed to improve energy efficiency of their building stock by implementing the energy performance of buildings directive (EPBD). Should higher energy efficiency result in better indoor environmental quality (IEQ), this policy could also be seen as an opportunity to improve public health across Europe.

Objectives: This paper focuses on the assessment of the effects of energy retrofits on occupant satisfaction with IEQ and health in multifamily buildings.

Methods: Data on occupant satisfaction with IEQ and health were collected from the occupants of 39 Finnish and 15 Lithuanian multifamily buildings (an average of five apartments per building, one adult per apartment) both before and after energy retrofits (such as improving thermal insulation, windows, heating and/or ventilation systems). Parallel to the data collected from the occupants, data on several IEQ parameters, including temperature, temperature factor, and air change rate, were collected from their apartments. Moreover, data from seven Finnish and five Lithuanian non-retrofitted control buildings were collected according to the same protocol.

Results: Occupant satisfaction regarding indoor temperature was associated with both retrofit status (OR 5.3, 95% CI 2.6-11.0) and measured IEQ parameters (indoor temperature OR 1.4 per 1 ^{o}C increase, temperature factor OR 1.1 per 1% increase, and air change rate OR 5.6 per 1/h increase). Additional positive associations were found between retrofit status and occupants reporting absence of upper respiratory symptoms (OR 1.8, 95% CI 1.1-2.9) as well as not missing work or school due to respiratory infections (OR 4.1, 95% CI 1.2-13.8), however, these associations were independent of the measured IEQ parameters.

Conclusions: There seems to be a strong subjective component related to the observed changes in occupant satisfaction with IEQ and health as a result of energy retrofitting in buildings. Further studies are needed to verify the actual mechanisms, as well as possible long term effects.

Keywords: apartment buildings, indoor air quality, noise, respiratory symptoms, sick leaves, sleeping problems, thermal comfort, ventilation

Background

Within the EU, the Energy Performance of Buildings Directive (EPBD) is a major force aiming to reduce energy consumption in the housing sector (EU Directive, 2010). The directive strives to have all new buildings be so-called nearly zero-energy buildings (nZEBs) by the end of 2020, while subjecting existing buildings during major renovations to meet minimum energy performance requirements tailored to the local climate. It is expected that more energy efficient buildings provide better living conditions and save money for all citizens. However, the progress made by EU Member States towards implementing EPBD requirements has been slower than expected, and there is a need to ensure that the EU's long-term climate objectives are not jeopardised (European Commission, 2013). Obstacles may include a lack of information among decision makers, building professionals and occupants regarding the potential benefits of improved energy efficiency, as well as apprehension caused by possible unknown risks.

Increased energy efficiency (EE) can translate to improved indoor climate and comfort for the residents, as reported by some follow-up studies (Buvik et al., 2011; Brown et al., 2011; Wilson et al., 2016; Francisco et al., 2017). However, adverse effects related to retrofit solutions have also been reported, such as increased noise levels due to unbalanced ventilation systems (Cali et al., 2011), and exposure to indoor pollutants related to reduced dilution air (Derbez et al., 2014). Overall, the housing sector has a pivotal role in both the mitigation of climate change and adapting to it. Potential for both positive and negative interactions between adaptation and mitigation strategies suggest that these strategies need to be carefully assessed and managed to achieve maximum benefits. As indicated by the World Health Organization (WHO, 2011), it is important to examine opportunities where health gains and sustainability objectives can be mutually reinforcing.

So far, there exists very a limited amount of research on how low-energy buildings will perform in practice. Collecting information directly from the occupants is also important. Occupant perception related to thermal, atmospheric, acoustic, and visual indoor environmental quality (IEQ) parameters are known to affect their behaviour as it relates to energy consumption (Larsen et al., 2010). For example, unsatisfactory thermal conditions may increase energy consumption by prompting occupants to increase use of heating, cooling, ventilation, or other mechanical systems (Andersen, 2009). Moreover, there are known associations between many IEQ parameters and occupant health; for example, exposure to increased levels of air pollutants is associated with respiratory health (Fisk, 2014). Satish et al. (2012) described statistically significant effects of exposure to low to moderate carbon dioxide (CO_2) concentrations on human decision-making performance, suggesting that direct adverse effects of CO_2 on human performance may be economically significant and limit energy-saving reductions in outdoor air ventilation per person in buildings.

Collecting information from the occupants using structured interviews or questionnaires can be useful when assessing ways to improve occupant satisfaction with their housing conditions, and also in larger scale population studies where sample size is sufficient for group level (statistical) analyses (e.g. Pekkonen et al., 2017). Limitations of occupant surveys include that they provide subjective measures prone to bias such as self-selection bias and misclassification (Rothman et al., 2008). However, self-reported health has been shown to correlate with clinical health (e.g . Marmot et al., 1995; Miilunpalo et al., 1997; Halford et al., 2012).

There exist a few energy retrofit intervention studies, which have included assessments of occupant satisfaction and health. In the UK, a review of the impacts the Warm Front program provided evidence that the home energy improvements conducted were accompanied by appreciable benefits in terms of use of living space, comfort and quality of life, as well as physical and mental well-being (Gilbertson et al., 2006). In Germany, the WHO Frankfurt housing intervention study concluded that retrofit and insulation activities did not appear to be in conflict with the health of residents (Braubach et al., 2008).

Outside Europe, a cluster randomised study was conducted to evaluate the effects of insulating existing houses in New Zealand. It was reported that insulating houses led to a significantly warmer, drier indoor environment, and resulted in improved self-rated health, less self-reported wheezing, fewer days off school and work, and fewer visits to general practitioners as well as a trend for fewer hospital admissions for respiratory conditions (Howden-Chapman et al., 2007). In addition, recent studies from the US have found weatherization and green healthy housing improvements associated with improved self-reported health (Jacobs et al., 2015, Francisco et al., 2017). However, previous studies have not linked the improved health outcomes to measured changes in IEQ, thus providing mainly anecdotal evidence possibly biased by subjective reactions to the modernization of the buildings, i.e. improved satisfaction with housing but not necessarily improved health per se.

This paper is focused on data collected from the occupants of retrofitted (case) and control buildings from Finland and Lithuania. As part of the INSULAtE-project, we have already reported significant changes in indoor thermal conditions, ventilation rates, and pressure differences in the dwellings, and concentrations of radon, nitrogen dioxide, formaldehyde, volatile organic compounds and particulate matter in indoor air, as well as fungal and bacterial concentrations in settled dust, some which could be attributed to the retrofit status of the studied multi-family buildings (Leivo et al., 2017a,b, 2018; Du et al., 2016). However, detailed analyses on occupant satisfaction with IEQ and health have not been conducted so far, thus being the main aim of this study. The secondary aim was to study whether such associations are dependent on the measured IEQ parameters.

Methods

Data were collected from a total of 46 Finnish and 20 Lithuanian multi-family buildings. Of these, 39 buildings in Finland and 15 in Lithuania were retrofitted during 2012-2015, while the remaining seven Finnish and five Lithuanian buildings were controls (i.e. not retrofitted during the course of the study). The buildings were located within a 300 km radius from Tampere in Finland, and the Kaunas region in Lithuania. An average of five apartments per building (315 from Finland and 99 from Lithuania) were recruited from volunteering occupants, who did not receive any compensation for their participation in the study.

Details about building characteristics and retrofit actions by country are presented elsewhere (Du et al. 2016, Leivo et al. 2017a). In short, buildings did not differ significantly by type, year of construction nor size of the apartments. Most buildings in Finland had mechanical ventilation, whereas all buildings in Lithuania had natural ventilation, which in some apartments had been improved with occupant-controlled, fan driven exhaust in the kitchen and natural or mechanical exhaust in the bathroom. Due to stricter building regulations until the 1990's, existing building stock in Finland has relatively high energy efficiency as compared to

Lithuanian buildings (Ministry of the Environment, 2017; Stankevicius et al., 2007). The most common retrofit actions in Finnish buildings were replacing windows and/or installing heat recovery to the existing exhaust ventilation system. In Lithuania, the most common retrofits involved adding thermal insulation to the walls and roof, replacing windows and glazing balconies, but did not typically include changes to the ventilation systems.

IEQ assessment was performed by trained investigators, who conducted measurements in each participating apartment. The assessment included monitoring indoor temperature (T) and relative humidity (RH); carbon dioxide (CO_2) and particulate matter ($PM_{2.5}$, PM_{10}); air change rate (ACR) and air pressure (ΔP) measurements; passive air sampling of nitrogen dioxide (NO_2), volatile organic compounds (VOC), formaldehyde (CH_2O), and radon (Rn); and the collection and analysis of fungi and bacteria concentrations in the settled dust. The assessment protocol (including QA/QC metrics) are described elsewhere (Du et al., 2016, 2015) and briefly summarized in the following paragraphs.

Indoor T and RH was continuously monitored in the living room with one hour resolution using data loggers (DT-172 logger, Shenzhen Everbest Machinery Industry Co., Ltd, China) for a minimum of two months during the heating season (in some cases the monitoring was extended to one year). In addition, Tc and RHc were monitored next to the coldest spot (detected by thermal camera or IR-thermometer, usually by balcony door), based on which "Temperature Factor", f_c= (Tc - outdoor T) / (indoor T - outdoor T) * 100 %, was calculated.

Concentrations of CO_2 were measured every minute during a 24-hour period with new factory calibrated monitors (HD21AB/HD21AB17, Delta OHM, Italy). Indoor and outdoor 24-hour $PM_{2.5}$ and PM_{10} concentration measurements were performed every minute using optical particle counters (OPCs, Handheld 3016 IAQ, Lighthouse Inc, USA). In addition, pressure differences (indoor – outdoor and indoor – staircase) and air flow through vents in the bathroom, kitchen or walk-in closet (if applicable) were measured.

Concentrations of NO_2 were sampled by a passive Difram100 Rapid air monitor (Gradko, Ltd., England) with one week exposure time. Concentrations of CH_2O and VOCs, including benzene, toluene, ethylbenzene and xylenes (BTEX), were sampled using Radiello™ Cartridge Adsorbents (Sigma-Aldrich) with one week exposure time. With respect to Rn, two different methods were utilized in order to adapt to the national guidelines for each country. In Finland radon samplers from the Finnish Radiation and Nuclear Safety Authority (STUK) were used with a sampling period of two months based on the alpha track method (Reisbacka, 2010). In Lithuania gamma dose rate measurements were used (Standard electrets E-PERMTM, Rad Elec Inc.) with one month sampling period (Pilkyte and Butkus, 2005) as suggested by the Lithuanian Radiation Protection Centre.

Settled dust was collected on 20 × 45 cm standardized-placed acquisition-surfaces, referred to as settled dust boxes (SDBs), for two months. After SDBs were collected from the homes, they were transported to the study centres, where the dust was vacuumed onto filter cassettes (0.45µm MCE filter membranes, Zefon International, US) for subsequent microbial analysis. The analysis was carried out in a sub-sample of the homes, using the quantitative polymerase chain reaction (qPCR) technique targeting selected fungal and bacterial groups (including concentrations of total fungi and both gram negative and gram positive bacteria) using previously published qPCR assays and approaches (Haugland et al., 2004; Torvinen et al., 2010; Kärkkäinen et al., 2010).

Information about housing and health was collected from the occupants by questionnaires developed and tested using previous national housing and health studies (Turunen et al., 2010, 2017). One adult per apartment was asked to fill in a questionnaire. The final questionnaire comprised of 49 questions related to the building and living environment; physical, biological, and chemical conditions; hygiene; occupant behaviour, health and well-being; and background information. Figure S1 presents a sample of the original questions, used for the dichotomized outcome variables as shown in Table 1.

With respect to selected outcome variables, where differences were observed on the group level, the results were further analysed using General Estimating Equations (GEEs) using IBM SPSS Statistics version 24. The models were fitted with unstructured covariance structure and binominal link-function. In these models, individual responders and buildings, as well as the time of the questionnaire were identified by the individual respondent's and building's ID (subject-variables), and pre/post-status (within subject-variable). The main factor was defined as pre/post * case/control status, and other factors included gender and history of smoking, while the respondents' age was included as a covariate. For selected outcomes, further modelling was performed by including tenure status and keeping pets indoors as additional factors, together with the type of ventilation system used. In addition, outdoor temperature and continuous IEQ variables (listed in Table 2) were included as possible covariates.

Selection of the IEQ variables to the models was carried out so that first, variables that were statistically significantly ($p < 0.05$) associated with the outcome variables were selected. In the following process, all selected variables were included in the model, based on which variable with the highest p-value was eliminated. The elimination procedure was repeated until all variables that were not significant at the level of 0.05 were eliminated. In order to make sure that significant variables were not lost because of covariance between one variable and another (eliminated) variable, each eliminated variable was then added to the preliminary models. If the variable was now significant, the variable was selected for the final model. The final models were fitted by including all statistically significant IEQ variables. The results are reported as odds ratios (ORs).

Results

From a total of 315 recruited apartments in Finland, 227 occupants (199 from retrofitted buildings, 28 from control buildings) participated in the first questionnaire, while 184 occupants (166 retrofitted, 18 controls) participated in the second questionnaire (response rate 72%, attrition rate 19%). From a total of 99 apartments from Lithuania, 55 occupants (41 retrofitted, 14 controls) participated in the first questionnaire, while 27 (all retrofitted) participated in the second questionnaire (response rate 56%, attrition rate 51%).

Background characteristics of the respondents and their apartments are shown in the supplementary Table S1, and thermal comfort, IEQ, and health characteristics are shown in Tables S2-S4. While group level differences before and after retrofits using the chi-square test are indicated in these tables, the test does not take into account the dependency between the samples, i.e. data clustering and the fact that in most cases the respondents after the retrofits were same as before the retrofits. Therefore, these test results were only used for screening purposes.

We also checked possible differences between the occupant characteristics in case and control buildings. In Finland, a larger proportion of the respondents from the case buildings were females, and kept furry pets indoors less frequently than the respondents from the control buildings. On the other hand, the respondents from the control buildings were significantly more often tenants, were younger, had lived in their current apartment a shorter period of time, and had less children living in their apartments. Mechanical air supply and wood burning fireplaces were less common in the case buildings before the retrofits. After the retrofits, the differences remained significant for the tenure status and the number of children living in the apartment. In addition, the respondents from the case buildings reported exercising more frequently. In Lithuania, the respondents from the control buildings were significantly more often tenants, and less frequently had pets or children living in their apartment.

After the retrofits, the respondents from the Finnish case buildings reported a higher proportion of apartments having covered balconies, trickle vents, and mechanical supply air, which correspond with the targeted energy retrofit actions. Saunas also became significantly more common in the case buildings after the retrofits. Respondents from the Lithuanian case buildings reported a smaller proportion of apartments having mechanical exhaust after the retrofits, which corresponds to the actual situation (i.e. most buildings had natural ventilation). Thermal comfort appeared to improve in the Lithuanian case buildings after the retrofits, while unpleasant odours were reported to lesser extent in Finnish case buildings. Respondents from both countries reported less environmental noise (related to traffic, industry etc.) after the retrofits, whereas respondents from Finnish buildings reported slightly more building related noise. Satisfaction with indoor air quality (IAQ) improved in both countries, and reports of respiratory symptoms, infections and missed work or school days appeared to have decreased after the retrofits.

Descriptive statistics related to the outcome variables selected for GEE modelling are shown in Table 1. Multi-category variables were dichotomized, as indicated in Figure S1. Descriptive statistics related to IEQ measurement data are presented in Table 2. As shown in Table 3, GEE models indicated significant associations between retrofit status and self-reported suitable indoor temperature in the winter, environmental (e.g. traffic, industry) and building related noise, satisfaction with IAQ, upper respiratory symptoms, and missing school or work due to respiratory infections. On the other hand, retrofit status was not associated with suitable indoor T in summer, sleeping problems, or general symptoms (e.g. headache, fatigue). Noise nuisance related to the building was significantly associated with the retrofit status in the Lithuanian sample, with an opposite trend in the Finnish sample.

Table 4 presents results from further analyses, where additional factors and covariates were included in the models for suitable indoor T, satisfaction with IAQ, sleeping problems, upper respiratory symptoms and missed school /work due to respiratory infections. Based on the results, occupants from the retrofitted buildings reported significantly more suitable indoor T during winter after the retrofits than before the retrofits (OR 5.3, 95% CI 2.6-11.0). In addition, satisfaction with indoor T was associated with gender, as well as measured indoor T (OR 1.4 per 1 °C increase), f_c (OR 1.1 per 1 % increase), and ACR (OR 5.6 per 1/h increase).

An association was also found between retrofit status and satisfaction with IAQ: occupants were more satisfied with IAQ after the retrofits than before the retrofits (OR 2.0, 95% CI 1.2-3.4). However, occupants from the control buildings were significantly more satisfied with IAQ than the occupants from the case buildings, based both on the first survey (OR 2.9) and the second survey (OR 6.0). Satisfaction with IAQ was also associated with the age of the respondent, as well as the pressure difference against the staircase (OR 1.1 per 1 Pa increase).

Retrofit status was not associated with sleeping problems. However, daily building related noise nuisance was associated with sleeping problems (OR 2.7, 95% CI 1.3-5.6), along with the age of the respondent.

The odds of not reporting upper respiratory symptoms increased after the retrofits (OR 1.8, 95% CI 1.1-2.9) as well as not missing school or work due to respiratory infections (OR 4.1, 95% CI 1.2-13.8). These outcomes were not significantly associated with any other factors or covariates, including measured IEQ parameters.

Results from the GEE models also indicated that after adjusting for age, gender, and history of smoking; there were significant differences between countries in reporting suitable temperature in winter, satisfaction with IAQ, and environmental and building related noise nuisance, as well as reporting upper respiratory symptoms. After including additional factors and covariates, respondents from Finland had significantly higher odds of being satisfied with IAQ and reporting upper respiratory symptoms compared to Lithuanian respondents (Table 4).

Discussion

We have collected a large data set including questionnaire data on occupant satisfaction with housing and health, as well as measurement data on several IEQ indicators before and after energy retrofits of multifamily buildings in Finland and Lithuania. Based on previous analyses we concluded that ventilation rates (l/s per person) were significantly higher after the retrofits in Finnish case buildings with mechanical exhaust ventilation (Leivo et al., 2017a). On the other hand, ventilation rates were significantly lower after the retrofits in Lithuanian case buildings, which did not have mechanical ventilation. In addition, indoor T, temperature factor, and RH increased significantly in Lithuanian case buildings (Leivo et al. 2018). We also found a statistically significant association in pressure difference against the staircase between pre and post retrofit measurements in Lithuanian case buildings (Leivo et al., 2017b). Moreover, it was previously reported (Du et al., 2016) that reductions observed in fungal and bacteria concentrations in settled dust could be attributed to retrofit status in Finnish buildings, whereas there was a significant increase in indoor air BTEX concentrations. In Lithuanian buildings, radon concentrations were significantly increased after the retrofits. It was hypothesized that these changes could explain possible differences in occupant satisfaction with IEQ and health.

Based on the current study, occupant perception of suitable indoor T in winter was positively associated with measured indoor T, f_c, and ACR. The results are similar with a field study of thermal comfort in low-income dwellings in England before and after energy efficient refurbishment, where the mean indoor temperature increased from 17.1 °C to 19.0 °C, leading to an increase in the proportion of households feeling thermally ‘comfortable’ or warmer from 36.4% to 78.7% (Hong et al., 2009). The independent association with f_c illustrates a potential to improve thermal comfort by adding insulation, which is likely to increase interior surface temperatures during winter, thus reducing asymmetric thermal radiation associated with thermal discomfort (Fanger et al., 1985). Also reduced air turbulence intensity should have a positive impact on the draught sensation (Airaksinen et al., 2004).

Based on our results, increased ventilation rates also associated with increased thermal comfort, which could be due to relatively high indoor temperatures in Finnish buildings. Also, use of mechanical ventilation in Finnish buildings, as well as decreased window opening (Table S2), could result in more controlled air flows.

Surprisingly, after including the three covariates in the GEE model, the association between self-reported suitable T and retrofit status became even stronger. It appears that while occupant perceived thermal comfort was associated with both objectively measured thermal conditions and ventilation, also occupant subjective perception and satisfaction with their housing and/or other (yet unrecognized) changes related to energy retrofits could lead to increased thermal comfort among the occupants.

Occupant satisfaction with IAQ was also associated with the retrofit status, but the effect was not as clear, as even bigger changes were observed among occupants from the control buildings. It was also found that air pressure difference against the staircase was associated with IAQ satisfaction. High negative pressure could result in impurities from other apartments, outside, and building structures being drawn inside the apartment, leading to a worsening perception of air quality (Airaksinen et al., 2004; Pessi et al., 2002; Emmerich et al., 2003). However, it appeared that changes observed between pre and post retrofit pressure differences (Leivo et al., 2017b) did not modify the association between the retrofit status and satisfaction with IAQ, as the corresponding parameter estimates did not change considerably.

Whereas retrofit status was not associated with sleeping problems, it was found that daily noise nuisance related to the buildings (ventilation, plumbing, electrical systems, lifts, etc.) were associated with sleeping problems. Our preliminary analyses had indicated a slight increase in occupants reporting building noise nuisance in Finnish case buildings, so system upgrades minimizing the possible noise nuisance are advisable. It was also found that the proportion of occupants reporting daily noise nuisance from the surrounding environment (traffic, industry, etc.) decreased in both countries after the retrofits, which could be related to better insulation and airtightness of the building envelope. However, this type of noise was not associated with sleeping problems in our study. Other studies have reported associations between environmental (incl. traffic) noise with annoyance, sleep disturbance, and cardiovascular health (Muzet, 2007; Münzel et al., 2014), thus energy retrofits could result in a noticeable co-benefit related to controlling environmental noise.

Finally, retrofit status was associated with self-reported respiratory symptoms and infections, which have been associated with IEQ indicators in previous studies (Hulin et al., 2012; Koistinen et al., 2008). In addition, we analysed missed work or school due to respiratory infections as a possible indicator of productivity. Whereas retrofit status was significantly associated with these outcomes, as well as with some changes in IEQ parameters as described earlier; we did not find direct links between these outcomes and any of the measured IEQ parameters. Therefore, the mechanisms related to changes in respiratory health and related productivity indicators as a result of building energy retrofits remain unclear. This could be partly related to sample size limitations.

Due to numerous factors that influence human health and well-being, a large sample size is needed to draw conclusions about the empirical relationships between housing conditions and occupant health. In our study, the sample size seemed sufficient to detect differences in 1) occupants' subjective perceptions on their housing conditions (e.g. satisfaction with indoor T and IAQ) as well as 2), respiratory symptoms and missed school or work due to respiratory infections before and after energy retrofits. However, our sample size does not appear to be sufficient to define relationships between the occupant health related responses (2) and objective IEQ measurements. Future studies can use the data presented to perform power calculations for finding effective sample size.

There are many methodological difficulties inherent in assessing satisfaction with IEQ and health which need to be carefully considered. For example, low response and high attrition rates can limit the possibility to draw conclusions and generalize results. In this study, the response rates were relatively good (75% in Finland and 56% in Lithuania), but the attrition rate, especially among the Lithuanian samples, was high (51%). Also, due to the demonstrative nature of this study, we could not match the retrofitted buildings with same number of control buildings. Including even a smaller sample of control buildings was beneficial, because it helped to detect some potentially false positive changes (i.e. where change was observed among cases but was also observed among controls, thus potentially unrelated to the retrofit). However, a larger sample of control buildings would have been desirable. Another issue is that occupants of the control buildings appeared to be less motivated to participate in the study, especially for the second round, which also limits the conclusions that can be made.

The subjective nature of occupant self-reporting is one of the challenges related to the interpretation of the results. In this study, we attempted to increase objectivity by using questions that could be validated (e.g. doctor diagnosed illnesses, missed work days), and linking occupant responses with objective measurements. Whether or not these attempts were effective, it appears that the results from occupant questionnaires are also valuable. Even objectively measured improvements in IEQ might not be regarded successful, if occupants did not perceive them well.

Some country level differences were seen in the occupant responses. For example, association between retrofit status and occupant reporting of suitable T in winter was much stronger in Lithuania, corresponding to measurable changes in indoor T. Noise nuisance related to the buildings appeared to be reduced among Lithuanian cases (with natural ventilation) whereas an opposite trend was seen among Finnish cases, which could be related to use of mechanical systems in Finnish buildings.

Lower odds of reporting weekly upper respiratory symptoms after retrofits were observed in Lithuanian cases, but the association was not significant (possibly due to small sample size). On the other hand, lower odds of not missing work or school were seen among Lithuanian cases (OR 1.3) as compared to Finnish cases (OR 2.3). Overall, the differences with respect to self-reported health could be related to numerous factors including differences in climate and culture, and further studies with larger samples size are needed to see if housing conditions could explain part of the observed differences.

As a whole, the INSULAtE-project has developed a comprehensive assessment protocol aiming to demonstrate impacts of improving energy efficiency in buildings on IEQ and occupant satisfaction with housing and health. As a part of the protocol we used a housing and health questionnaire, which could be utilized when assessing the effects of improving energy efficiency of the housing stock on occupant health and wellbeing. It appears that the questionnaire can be used when assessing effects of energy retrofits on occupant satisfaction with thermal conditions, but possible effects linking occupant health and productivity to objectively measured changes in IEQ parameters need to be studied with a larger sample size. It should also be noted that long-term effects have not been studied so far.

Conclusions

Energy retrofits of multifamily buildings were associated with mostly positive changes in occupant satisfaction with indoor temperature, daily noise nuisance, upper respiratory symptoms and missed work or school due to respiratory infections. There seems to be a strong subjective component related to the observed changes in occupant satisfaction with housing and health; further studies are needed to verify the actual mechanisms, as well as possible long-term effects.

Declarations

Ethics approval and consent to participate: The study plan was evaluated and approval was obtained from the National Institute for Health and Welfare’s Ethical Research Working Group in Finland as well as Approval to Conduct Biomedical Research in Lithuania. Informed consents to participate in the study were obtained from the participants.

Availability of data and material: The data that support the findings of this study are available from the National Institute for Health and Welfare, Finland (THL), but restrictions apply to the availability of these data, which were used under license for the current study, and are not publicly available. Data are however available from the authors upon reasonable request and with permission from THL.

Competing interests: The authors declare that they have no competing interests.

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Authors' contributions: UHS designed and coordinated the study, analyzed data, and wrote the first draft of this manuscript; MP contributed to designing of the occupant questionnaires and data collection; VL contributed to study design, coordinated field studies in Finland, and interpretation of the results; TP coordinated field studies in Lithuania and contributed to data collection and interpretation of the results; MT contributed to project management, data collection, and interpretation of the results; MK contributed to data collection and interpretation of the result; AA contributed to data collection and interpretation of the results; DM contributed to study design, overseeing the field studies in Lithuanian, and interpretation of the results.

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Table 1: Descriptive statistics for selected occupant IEQ satisfaction and health outcomes.

	Finland				*Lithuania*		
	Control		*Study*		*Control*	*Study*	
	Pre	*Post*	*Pre*	*Post*	*Pre*	*Pre*	*Post*
	N(%)	*N(%)*	*N(%)*	*N(%)*	*N(%)*	*N(%)*	*N(%)*
Suitable temperature in summer	14 (50)	12 (67)	118 (57)	95 (56)	8 (30)	18 (44)	15 (56)
Suitable temperature in winter	17 (61)	9 (50)	130 (63)	113 (67)	5 (31)	14 (34)	21 (78)
Building noise daily or almost daily	5 (19)	4 (25)	23 (12)	27 (18)	10 (63)	20 (49)	5 (19)
Environmental noise daily or almost daily	3 (11)	1 (6)	51 (27)	28 (18)	11 (69)	24 (59)	10 (37)
Satisfied with IAQ	14 (50)	9 (53)	42 (21)	62 (37)	1 (8)	9 (24)	9 (33)
No daily or weekly sleeping problems	21 (75)	13 (77)	143 (76)	116 (74)	5 (46)	26 (81)	13 (68)
No daily or weekly general symptoms	23 (82)	14 (88)	127 (70)	105 (82)	7 (64)	27 (79)	16 (70)
No daily or weekly upper respiratory symptoms	24 (86)	13 (81)	111 (59)	114 (70)	7 (64)	28 (93)	17 (94)
Did not miss work or school	24 (86)	14 (82)	124 (79)	127 (89)	9 (75)	19 (76)	17 (85)

Table 2. Descriptive statistics related to IEQ measurements.

	Finland				Lithuania			
	Control		Case		Control		Case	
	1st	2nd	1st (pre)	2nd (post)	1st	2nd	1st (pre)	2nd (post)
	Mean, Md (SD)[1]	Mean, Md (SD)[1]	Mean, Md (SD)[1]	Mean, Md (SD)[1]	Mean, Md (SD)[1]	Mean, Md (SD)[1]	Mean, Md (SD)[1]	Mean, Md (SD)[1]
***T_{out}* [ºC]**	-6.3, -4.9 (4.3)	-0.8, -0.6 (4.2)	2.2, 2.0 (5.3)	3.1, 2.0 (5.0)	0.9, 3.0 (4.6)	9.3, 9.4 (2.2)	-1.4, -2.3 (4.0)	1.9, 1.3 (3.1)
***RH_{out}* [%]**	80.0, 87.2 (9.8)	81.6, 89.1 (9.2)	76.3, 74.3 (8.5)	80.0, 79.3 (7.7)	75.0, 73. 9 (4.0)	66.7, 65.8 (2.3)	76.8, 78.2 (6.3)	77.0, 76.0 (6.5)
***T_{in}* [ºC]**	22.6, 22.6 (0.9)	22.4, 22.4 (1.0)	22.8, 22.8 (1.2)	22.7, 22.7 (1.2)	20.0, 20.0 (1.1)	21.2, 21.1 (1.5)	19.5, 19.5 (1.8)	20.3, 20.4 (1.3)
***RH_{in}* [%]**	19.8, 18.1 (5.4)	23.9, 24.0 (5.5)	28.8, 28.6 (7.1)	30.1, 30.2 (6.8)	43.9, 42.2 (7.5)	46.8, 47.9 (6.2)	43.3, 43.6 (10.9)	48.7, 48.1 (8.9)
f_c ***[%]***	89.6, 89.7 (5.2)	89.6, 90.4 (5.9)	87.9, 89.6 (6.4)	88.0, 88.3 (8.1)	92.8, 95.3 (6.6)	87.8, 88.6 (10.9)	91.0, 92.8 (7.9)	93.1, 94.4 (7.7)
ACR [h^{-1}]	0.6, 0.6 (0.2)	0.5, 0.4 (0.2)	0.4, 0.4 (0.2)	0.5, 0.4 (0.2)	0.4, 0.4 (0.2)	0.3, 0.3 (0.1)	0.4, 0.3 (0.3)	0.3, 0.3 (0.3)
Max CO_2 [ppm]	754, 740 (150)	817, 709 (496)	961, 851 (384)	912, 808 (402)	1581, 1570 (527)	1315, 1326 (569)	1572, 1410 (806)	1690, 1489 (829)
***ΔP_{Stair}* [Pa]**	-3.8, -3.6 (3.5)	-4.9, -5.5 (5.3)	-7.9, -5.6 (9.0)	-7.9, -6.1 (7.1)	-3.1, -1.4 (3.9)	-2.4, -1.7 (2.3)	-2.1, -1.9 (1.9)	-0.1, -0.5 (3.1)
***ΔP_{Out}* [Pa]**	-12.9, -11.5 (5.0)	-14.0, -11.6 (9.5)	-18.1, -13.7 (17.1)	-19.2, -17.5 (15.1)	-6.3, -4.1 (6.9)	-0.8, -1.6 (3.8)	-4.0, -2.5 (4.7)	-2.8, -2.2 (6.8)
***NO_2* [µg/m³]**	3.9, 3.9 (1.6)	5.7, 4.9 (2.9)	7.1, 6.1 (3.9)	6.8, 6.0 (4.6)	15.0, 16.0 (7.1)	13.1, 13.8 (5.3)	13.7, 11.9 (8.1)	13.8, 11.5 (8.1)
***Rn* [Bq/m³]**	43.3, 40.0 (25.5)	50.8, 40.0 (29.7)	71.2, 50.0 (70.5)	66.7, 50.0 (56.3)	20.7, 14.0 (17.0)	16.8, 18.0 (5.5)	32.4, 28.0 (25.0)	43.9, 38.0 (26.8)
***CH_2O*, [µg/m³]**	16.4, 15.9 (5.1)	13.4, 13.5 (3.5)	21.6, 18.4 (13.0)	19.4, 16.7 (8.8)	16.2, 16.5 (6.1)	33.0, 32.9 (10.9)	25.5, 24.1 (10.6)	31.0, 28.0 (13.4)
BTEX, [µg/m³]	7.7, 5.4 (6.3)	8.9, 7.0 (4.5)	9.8, 6.7 (12.1)	10.8, 9.1 (7.0)	11.4, 7.3 (12.5)	16.0, 7.7 (23.4)	26.6, 16.0 (27.3)	24.5, 19.4 (12.9)
lg10 (fungi) [cells/m³]	2.3, 2.2 (0.6)	2.3, 2.1 (0.6)	2.7, 2.7 (0.6)	2.1, 2.0 (0.7)	3.5, 3.6 (0.6)	4.1, 4.1 (0.8)	3.4, 3.3 (1.0)	3.4, 3.3 (0.6)
lg10(gram+) [cells/m³]	4.0, 3.8 (0.5)	3.6, 3.2 (0.9)	3.8, 3.8 (0.7)	3.2, 3.1 (1.1)	4.5, 4.6 (0.7)	4.9, 5.2 (0.7)	4.1, 4.3 (1.2)	4.4, 4.5 (0.8)
lg10 (gram-) [cells/m³]	3.5, 3.6 (0.6)	3.3, 3.2 (0.8)	3.9, 3.9 (0.7)	3.0, 3.1 (1.0)	4.6, 4.8 (0.6)	4.7, 4.6 (0.5)	4.2, 4.5 (1.2)	4.4, 4.4 (0.7)
***$PM2.5_{in}$* [µg/m³]**	6.0, 4.4 (5.9)	5.2, 2.3 (5.8)	8.3, 5.3 (14.7)	8.5, 4.3 (19.1)	8.8, 6.6 (5.1)	5.4, 5.4 (1.9)	12.4, 10.6 (14.4)	12.6, 9.8 (14.4)
***$PM10_{in}$* [µg/m³]**	17.0, 11.9 (14.9)	16.9, 9.6 (23.2)	22.0, 14.6 (27.3)	17.8, 12.4 (21.3)	20.2, 17.8 (15.4)	17.4, 18.3 (6.1)	22.5, 18.5 (19.4)	30.1, 24.5 (25.7)
PM2.5 I/O[2]	1.5, 0.8 (1.3)	2.0, 1.1 (2.0)	1.7, 0.9 (3.4)	2.7, 0.9 (6.5)	0.7, 0.6 (0.4)	0.9, 1.0 (0.3)	1.4, 0.7 (2.6)	0.9, 0.6 (1.2)
PM10 I/O[2]	2.0, 1.3 (2.0)	1.6, 0.8 (1.4)	2.1, 1.0 (3.8)	2.5, 1.3 (3.6)	1.1, 0.8 (1.1)	1.4, 1.3 (0.6)	1.7, 0.8 (2.4)	1.1, 0.9 (1.1)

[1] 5th and 95th percentiles are reported by Du et al. 2016 [2] Indoor / Outdoor ratio

Table 3. Associations between retrofit status and occupant satisfaction with IEQ and health.

Crude (adjusted only for country)		Adjusted for age, gender & smoking		
	All	All	Finland	Lithuania
	OR (95% CI)[1]	OR (95% CI)[1]	OR (95% CI) [1]	OR (95% CI)[1]
Suitable temperature in summer				**Crude[2]**
Control post	1.40(0.52-3.76)	1.39(0.48-4.01)	1.23(0.43-3.55)	-
Control pre	0.85(0.44-1.63)	0.92(0.47-1.80)	0.76(0.34-1.68)	1.23 (0.39-3.88)
Case post	1.05(0.78-1.41)	1.03(0.77-1.39)	0.90(0.65-1.25)	2.26 (1.07-4.76)
Suitable temperature in winter				
Control post	0.61(0.25-1.51)	0.55(0.21-1.46)	0.49(0.17-1.33)	-
Control pre	0.84(0.44-1.59)	0.90(0.47-1.74)	0.91(0.41-2.04)	1.12(0.31-4.08)
Case post	**1.47(1.02-1.21)**	**1.53(1.03-2.26)**	1.11(0.73-1.68)	**8.72(2.75-27.63)**
Building noise				
Control post	2.54(0.93-6.93)	2.40(0.88-6.57)	2.52(0.86-7.44)	-
Control pre	1.71(0.83-3.53)	1.33(0.60-2.99)	1.13(0.34-3.80)	1.62(0.47-5.59)
Case post	1.08(0.71-1.64)	1.07(0.69-1.66)	1.53(0.90-2.60)	**0.38(0.17-0.84)**
Environmental noise				
Control post	0.20(0.04-1.04)	0.19(0.03-1.05)	0.14(0.12-1.30)	-
Control pre	0.71(0.36-1.38)	0.62(0.30-1.28)	0.33(0.10-1.15)	1.12(0.31-4.07)
Case post	**0.60(0.39-0.91)**	**0.58(0.38-0.88)**	0.67(0.42-1.08)	**0.38(0.15-0.92)**
Satisfied with IAQ				
Control post	**3.25(1.20-8.76)**	**3.52(1.26-9.84)**	**4.34(1.54-12.22)**	-
Control pre	**2.06(1.00-4.23)**	**2.31(1.12-4.79)**	**3.87(1.70-8.79)**	0.31(0.02-4.03)
Case post	**2.09(1.46-3.01)**	**2.11(1.47-3.04)**	**2.21(1.49-3.28)**	1.57(0.48-5.14)
No sleeping problems				**Crude[2]**
Control post	1.01(0.34-3.02)	0.96(0.31-2.91)	1.16(0.36-3.75)	-
Control pre	0.62(0.30-1.25)	0.52(0.25-1.08)	0.81(0.33-1.98)	0.20 (0.05-0.85)
Case post	0.85(0.57-1.27)	0.89(0.57-1.34)	0.98(0.62-1.55)	0.42 (0.15-1.18)
No general symptoms				
Control post	3.31(0.77-14.31)	3.77(0.86-16.57)	4.74(0.92-24.51)	
Control pre	1.39(0.64-3.01)	1.48(0.67-3.27)	2.34(0.86-6.37)	0.45(0.10-2.04)
Case post	0.94(0.66-1.34)	0.98(0.68-1.42)	1.06(0.70-1.60)	0.95(0.35-2.60)
No upper respiratory symptoms				
Control post	1.94(0.64-5.94)	1.95(0.66-5.80)	2.67(0.79-8.98)	-
Control pre	1.73(0.75-3.99)	1.64(0.71-3.76)	**3.95(1.35-11.57)**	**0.09(0.01-0.78)**
Case post	**1.68(1.19-2.37)**	**1.70(1.19-2.42)**	**1.72(1.20-2.49)**	2.67(0.27-26.17)
Did not miss work or school				
Control post	1.49(0.37-6.07)	1.65(0.28-9.93)	1.83(0.29-11.77)	-
Control pre	1.42(0.59-3.41)	1.67(0.62-4.50)	1.96(0.56-6.82)	0.94(0.16-5.47)
Case post	**2.12(1.27-3.53)**	**2.29(1.30-4.04)**	**2.37(1.31-4.30)**	1.25(0.18-8.92)

[1]Reference group (OR=1): case buildings before retrofits

[2] Background variables could not be included

Table 4. GEE models including respondents' background and selected IEQ variables.

	Suitable indoor T in winter	Satisfied with IAQ	No sleeping problems	No upper respiratory symptoms	Did not miss school or work
	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)
Gender					
Female	**0.33 (0.15-0.73)**	0.88 (0.45-1.74)	0.56 (0.28-1.12)	0.41(0.20-0.84)	1.22 (0.46-3.23)
Male	1.00	1.00	1.00	1.00	1.00
Smoking					
Never smoked	1.35 (0.67-2.72)	1.27 (0.63-2.58)	1.47 (0.76-2.84)	**1.79 (1.04-3.06)**	1.13 (0.42-3.02)
Smoking currently or previously	1.00	1.00	1.00	1.00	1.00
Tenure status					
Other	0.48 (0.11-1.99)	4.51 (1.20-16.96)	0.33 (0.09-1.15)	0.94 (0.21-4.16)	0.63 (0.08-4.78)
Rent	0.89 (0.32-2.50)	0.75 (0.21-2.62)	0.77 (0.30-1.94)	0.77 (0.33-1.79)	0.72 (0.15-3.52)
Own	1.00	1.00	1.00	1.00	1.00
No furry pets	1.77 (0.67-4.70)	0.70 (0.30-1.64)	0.91 (0.34-2.42)	1.58 (0.64-3.90)	1.85 (0.50-6.86)
Age	1.00 (0.98-1.02)	**1.02 (1.00-1.05)**	**0.98 (0.65-4.54)**	0.98 (0.96-1.00)	1.02 (0.99-1.05)
Ventilation system					
Mechanical	1.00 (0.25-3.95)	0.60 (0.16-2.29)	1.72 (0.65-4.54)	1.27 (0.45-3.62)	1.40 (0.33-5.92)
Natural	1.00	1.00	1.00	1.00	1.00
Country					
Finland	1.13 (0.21-5.93)	**4.53 (1.11-18.51)**	0.79 (0.25-2.43)	**0.28 (0.09-0.90)**	0.70 (0.14-3.44)
Lithuania	1.00	1.00	1.00	1.00	1.00
Case status					
Control post	0.26 (0.05-1.30)	**5.99 (1.03-34.93)**	3.83 (0.82-17.89)	1.78 (0.34-9.30)	0.70 (0.05-9.82)
Control pre	0.58 (0.18-1.82)	**2.85 (1.15-7.10)**	0.83 (0.33-2.10)	0.90 (0.32-2.53)	0.66 (0.20-2.23)
Case post	**5.33 (2.58-10.99)**	**1.98 (1.16-3.36)**	1.12 (0.59-2.10)	**1.82 (1.13-2.93)**	**4.08 (1.20-13.83)**
Case pre	1.00	1.00	1.00	1.00	1.00
Building noise almost daily	-	-	**2.71 (1.30-5.64)**	-	-
No noise	-	-	1	-	-
Tout [°C]	**0.86(0.80-0.93)**	0.96 (0.88-1.04)	-	0.97 (0.90-1.05)	0.99 (0.90-1.10)
T [°C]	**1.44 (1.06-1.96)**	-	-	-	-
f_c ***[%]***	**1.09 (1.03-1.16)**	-	-	-	-
ACR [1/h]	**5.60 (1.01-31.19)**	-	-	-	-
ΔP Stair [Pa]	-	**1.07 (1.02-1.12)**	-	-	-