The relation between indoor air quality in a bedroom and sleep quality of ageing adults

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ABSTRACT

Research on the effect of indoor air quality (IAQ) on sleep quality is limited. Furthermore, most research has been conducted with students. Therefore, the effect of IAQ (CO_2 concentration as proxy) on the sleep quality of ageing adults was investigated.

Twenty-two volunteers were studied during two periods of four consecutive nights. Each period at a different setting of a mechanical ventilation system (Low/High). IAQ was measured continuously. Indices of sleep quality were analyzed via actigraphy and questionnaires. Perceived IAQ was investigated as well.

A significant difference in CO_2 concentration was obtained for the two ventilation settings investigated. Objectively measured sleep quality, as well as subjective outcomes, did not differ when comparing both settings. At high setting, the perceived IAQ was improved. From the data gathered, it could be concluded that older people (>55 year) experienced more nightly awakenings, and a significantly better depth of sleep. Women judged the air quality significantly lower when compared to men.

INTRODUCTION

The European Energy Performance of Buildings Directive has given the impetus for the regulations to reduce the energy consumption in buildings (RVO, 2019), presently known as the NZEB (nearly Zero Energy Building) regulations. They will be introduced in The Netherlands in 2021 (RVO, 2020). To meet the newly defined requirements, insulation and airtightness will be important design requirements.

With better airtightness, reliable and sufficient ventilation becomes more important. Poor ventilation can lead to high indoor carbon dioxide (CO_2) concentrations, which generally is used as a proxy for assessing the Indoor Air Quality (IAQ). The ASHRAE standard recommends a maximum CO_2 concentration level at 700 parts per million [ppm] above outdoor level. With an outdoor level of 400 ppm, 1100 ppm is regarded acceptable for indoors. This mainly refers to the perceived acceptability of the air quality due to bio-effluents (ANSI/ASHRAE, 2019). Regarding the Dutch Building Decree, the regulations require a minimum of 25 m^3/h per person, which assumes an acceptable CO_2 concentration near 1200 ppm (NEN, 2001). The European standard EN 15152 recommends for newly built and renovated homes (category II) a maximum CO_2 concentration of 500 ppm above outdoors. For existing buildings (category III) a CO_2 concentration of 800 ppm above outdoors is recommended (NEN, 2007).

Insufficient ventilation, and therefore a high CO_2 concentration, can have a negative effect on health (Sundell, 2011) (Roelofsen, 2012). Investigations in homes with mechanical ventilation systems with heat recovery showed that higher ventilation rates were associated with fewer health problems (Jongeneel, Bogers, & van Kamp, 2011).

The effect of ventilation on the IAQ in a bedroom and on the sleep quality of a person is not broadly investigated, e.g. (Strøm-Tejsen, Zukowska, Wargocki, & Wyon, 2016). Mishra et al. concluded that lower CO_2-levels (717 ppm compared to 1150 ppm) implied better sleep depth, sleep efficiency and lesser number of awakenings (Mishra, van Ruitenbeek, Loomans, & Kort, 2018). A more recent study, where the IAQ was changed by opening/closing a window (CO_2 concentration of 1656 ppm with the window closed compared to 637 ppm with an open window), concluded that the participants reported better sleep quality when sleeping with quieter surroundings (windows closed) (Liao & Laverge, 2019). The results from the window open situation (lower CO_2 concentration), however, did not show an improvement in sleep quality. More data is needed to better identify the potential of IAQ on sleep quality.

The identified studies on sleep quality and IAQ (Mishra, van Ruitenbeek, Loomans, & Kort, 2018) (Liao & Laverge, 2019) (Strøm-Tejsen, Zukowska, Wargocki, & Wyon, 2016) influenced the IAQ through natural air supply. Therefore, it was not possible to control the air intake. The natural air supply also influenced the temperature and noise level. To arrive at a controlled ventilation rate and limit the influence of outdoor temperature and noise levels, in this study a mechanical ventilation system with heat recovery (MVHR) was used to influence the CO_2 level.

In addition, the studies from Mishra et.al., Liao et. al. and Strøm-Tejsen et.al. were conducted with students.

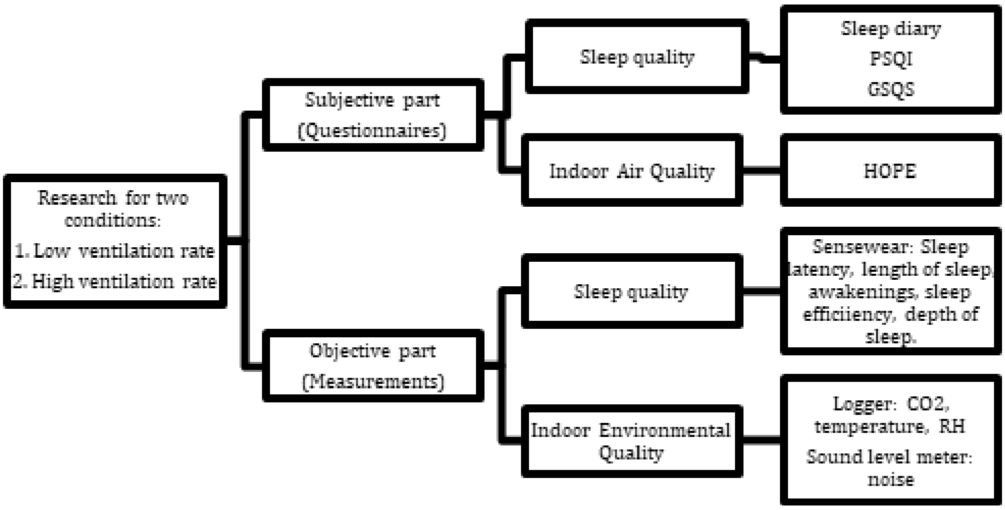

Figure 1: Study design for the two bedroom conditions: 1. Low ventilation rate 2. High ventilation rate.

However, the majority of our population are middle-aged men and women, leading an orderly life.

The objective of the present study therefore was to examine the relation between indoor air quality and the sleep quality of ageing adults. Similar to the other studies, CO_2 is set as proxy for the IAQ. The change in CO_2-concentration has been realized with a MVHR system, to create as constant conditions as possible.

METHOD

Multiple case-controlled study

Sleep quality and IAQ were studied for two different bedroom indoor environment conditions. These conditions were realized by two different settings of the MVHR-system (Figure 1). The first condition was with the MVHR system set at a low ventilation rate (LVR), level 1, and the second condition was with the system set at a high ventilation rate (HVR), level 3.

The indoor air quality was assessed objectively via measurement of the CO_2 level, temperature, relative humidity and noise. The sleep quality was monitored by measuring: sleep efficiency, sleep latency, length of sleep, awakenings and depth of sleep with the use of an actigraph armband (Sensewear). Actigraphy is a well-validated method for field studies of sleep (Kushida, et al., 2001). In addition, the perceived indoor air quality and the sleep quality were measured subjectively with the use of questionnaires. For each setting (LVR/HVR), measurements were conducted during a period of four consecutive nights (each Monday until Friday; so two weeks in total). The bedroom door and windows were closed during the night.

Table 1: Ventilation rate [m^3/h] and Air Change per Hour (ACH [h^{-1}]) for low and high ventilation rate at Location A and Location B.

	Location A		Location B	
	LVR	HVR	LVR	HVR
Ventilationrate [m^3/h]	41.6 ±14.1	91.5 ±25.1	15.2 ±11.5	30.8 ±22.8
ACH [h^{-1}]	1.5 ±0.5	3.3 ±0.8	0.5 ±0.3	1.0 ±0.6

Location

Subjects who volunteered for this study all lived in an apartment, and all apartments were equipped with a similar MVHR system. The measurements were performed in their normal bedroom environment. Participants from apartment buildings at two different locations, though both situated in the central part of The Netherlands, were selected. The locations are further indicated as Location A and Location B. The ventilation rate and the air change per hour (ACH) for the two ventilation settings at the locations A and B, are shown in Table 1.

Table 2: Demographics and the bedroom volume.

	Location A	Location B	Overall
Number of subjects [n]	12	13	25
Male [n]	5	6	11
Female [n]	7	7	14
Age (mean,SD) [year]	45 ±14.1	54 ±21.8	50 ±18.9
Volume bedroom (mean, SD) [m^3]	28.3 ±5.4	30.8 ±5.0	29.6 ±5.4

Subjects

In total 275 people (ageing adults) were approached at the two different locations. As the research was intensive, interest for participation was less high than hoped for, hence the need for two distinct locations A and B. The intention was to include at least 30 participants. This was not realized. See Table 2 for the details of the characteristics of the participating subjects per location and in total.

The subjects who participated did not use sleep medication or have sleep related health issues. During the measurements, the subjects were asked not to consume alcoholic beverages, because this can influence the sleep (Singleton & Wolfson, 2009). All participants gave their written consent with the study and were free to withdraw from the research at any time without providing a reason.

Measurements

Both the indoor air quality and the sleep quality were objectively assessed through measurements in the bedroom of the participants. The CO_2-concentration (0-5000 ppm; ±50 ppm), temperature (5-45°C; ±0.4°C) and relative humidity (0-100%; ±2%) were measured during the nights with a sensor (Eltek transmitter) at a five-minute interval. Background noise from the ventilation system was measured over a 10 sec interval, near the inlet and at the sleeping position (0-100 dB; ±1 dB). A set of instruments was applied in order to be able to perform measurements in parallel in different apartements. Before the execution of the measurements all equipment was compared to each other. The sensors were placed about 1.5 meters from the subject's pillow to avoid participants breathing directly upon the sensors

During the night, the participants wore a Sensewear armband, which calculates, at one-minute interval, activity level and the metabolism, from which the sleep latency, length of sleep, number of awakenings and the sleep efficiency can be derived.

Questionnaires

Questionnaires were applied to measure the sleep quality and the perceived indoor air quality subjectively. The questionnaire to measure the IAQ is based on the validated list that was developed in the Health Optimization Protocol for Energy-Efficient Buildings (HOPE) project (Hope, 2001). The questions were filled in daily, in the morning.

The Pittsburgh Sleep Quality Index (PSQI) (Buysse, Reynolds, Monk, Berman, & Kupfer, 1988) rates sleep over longer periods of time. The ten questions of the PSQI were filled in before the experiment, after the first week of measuring in the first setting (High/Low ventilation rate), and after the second week of measuring, with the second setting. The Groningen Sleep Quality Scale (GSQS) is a daily questionnaire with 15 true or false questions (Mulder, et al., 1980). This questionnaire was filled in every morning. Finally, a sleep diary was used to indicate when participants went to sleep and when they woke up. The sleep latency, length of sleep, number of awakenings and sleep efficiency have been derived from the sleep diary. The sleep diary was filled in every morning.

The measurement protocol and application of the questionnaires is in line with (Mishra, van Ruitenbeek, Loomans, & Kort, 2018).

Measurement period

The measurements were conducted in the heating season, because use of windows in the apartment will be minimal. The measurements at Location A were conducted in March and April 2019, at Location B in October and November 2019.

Data analysis

Both Excel and Python were used for descriptive analyses and creating graphs. The collected data was analyzed statistically with help of IBM SPSS statistics 26. In the statistical analysis, normality was tested with the Shapiro-Wilk's test. Next, it was determined if the outcomes for the two ventilation settings were significantly different from each other. The Paired

Table 3: Average (and SD) temperature [°C], relative humidity [%], CO_2-concentration [ppm] and noise [dB] for each location and ventilation condition, and the difference between the two locations.

	Location A			Location B			Difference Location A – Location B	
	LVR	HVR	Difference *p*-value	LVR	HVR	Difference *p*-value	LVR *p*-value	HVR *p*-value
Bedroom								
Temperature [°C]	19.2 ±0.9	19.4 ±0.8	.348	19.1 ±0.8	18.9 ±0.7	.986	.331	.689
RH [%]	49.2 ±3.9	46.7 ±2.5	**.016**	59.4 ±10.0	52.8 ±5.4	.148	**.032**	**.023**
CO_2 [ppm]	862 ±162	680 ±106	**< .001**	1409 ±412	1007 ±245	**< .001**	**.005**	**.010**
Noise [dB]	34.6 ±1.8	39.0 ±3.7	**.003**	36.7 ±1.1	38.9 ±1.5	**< .001**	**.027**	.936

Sample T-test was used for normally distributed parameters, while Wilcoxon Signed-rank test was used for non-normal distributed data. All comparisons reported in the results are two-tailed with a significant p-value of .05. Data are presented as mean values ±standard deviation. Correlations were assessed through the Pearson correlation coefficient. At minimum moderate correlations were strived for, represented by values>0.4 for objective data and >0.3 for subjective data at p-values <.05. Knowledge from earlier research (Mishra, van Ruitenbeek, Loomans, & Kort, 2018) was used to guide the analysis.

Because a significant difference was observed for the low and high ventilation rate (both $p < .001$) between Location A and Location B (see also Table 1), the two samples could not be regarded as one group. Therefore, Location A and Location B have been analyzed and described separately.

RESULTS

In total 25 people participated in the research. However, in the analysis, data were included from 22 subjects. Two subjects decided to resign during the measurement period, and one person was excluded because of a power outlet of the measurement equipment.

Measurements

Table 3 presents the measured conditions (temperature, relative humidity [RH], CO_2-concentration and sound pressure level) for locations A and B at high (HVR) and low ventilation rate (LVR).

There were no significant differences in bedroom temperature between the two ventilation settings for either location. Between the locations there was also no significant difference in temperature measured. For the relative humidity, a significant difference was found for Location A when comparing the two settings.

The average CO_2-concentration at Location A was significantly lower at a high ventilation rate as compared to the low ventilation rate. However, a large individual variation at low ventilation rate (486 to 1044 ppm) as well as at high ventilation rate (429 to 825 ppm) was found. This large individual variation is presented in Figure 2 for all 11 subjects of Location A.

Also for Location B, the average CO_2-concentration was significantly lower at a high ventilation rate. Again, large individual variations were recorded (625 to 2018 ppm at a low ventilation rate; 505 to 1342 ppm at a high ventilation rate). This large individual variation is presented in Figure 3 for the 11 subjects of Location B.

While subjects were in bed, the CO_2-concentration remained rather constant, although a gradual increase during the first two hours was observed in the bedrooms at a low ventilation rate (Figure 4).

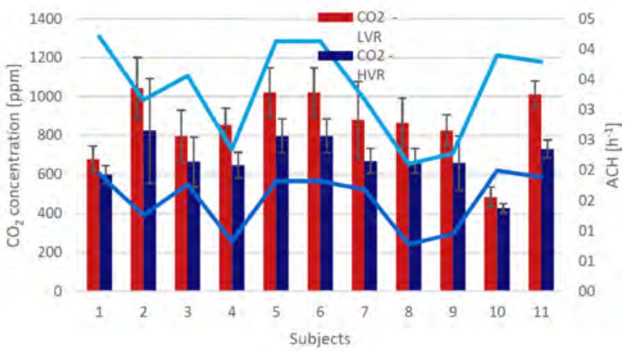

Figure 2: Average CO_2-concentration [ppm] and ACH [h-1] in the bedroom of each subject of Location A.

Table 4: Average (and SD) of sleep quality for each location and condition, measured by the Sensewear, and the difference between the two locations.

	Location A			Location B			Difference Location A - Location B	
	LVR	HVR	Difference *p*-value	LVR	HVR	Difference *p*-value	LVR *p*-value	HVR *p*-value
Sensewear								
Lying down [hr]	6.8 ±0.7	6.8 ±1.3	.872	8.1 ±0.9	8.3 ±1.0	.500	.093	.479
Length of sleep [hr]	5.7 ±0.6	5.8 ±1.1	.709	6.9 ±0.8	6.7 ±1.0	.450	**.045**	.409
Latency [mn]	72 ±44	62 ±44	.206	14 ±6.8	22 ±27.2	.278	**.033**	**.035**
Awakenings [n]	5.3 ±3	5.0 ±3.2	.778	7.1 ±2.3	6.9 ±3.1	.773	.414	.690
Efficiency [%]	83 ±9.5	85 ±9.2	.115	85 ±5.9	81 ±9.4	**.027**	.286	.980

Table 5: The Hope, PSQI, GSQS and sleep diary outcomes for both ventilation conditions for the two locations (average, SD), and the difference between the two locations.

	Location A			Location B			Difference Location A - Location B	
	LVR	HVR	Difference *p*-value	LVR	HVR	Difference *p*-value	LVR *p*-value	HVR *p*-value
Hope (10-66)	29.5 ±8.5	29.6 ±8.3	.982	26.2 ±7.9	25.6 ±7.3	.718	.374	.182
Temperature (1-28)	11.8 ±4.2	12.6 ±3.6	.465	10.7 ±4.3	11.8 ±3.9	.206	.678	.668
IAQ (1-28)	15.2 ±4.2	14.2 ±3.9	.307	13.8 ±4.3	11.8 ±3.5	**.035**	.362	.065
PSQI (0-21)	5.7 ±1.7	5.7 ±5.3	.895	4.2 ±2.2	4.4 ±2.1	.714	.199	.190
Quality of sleep (1-7)	2.9 ±0.5	2.9 ±0.9	.920	3.4 ±0.4	3.4 ±0.4	.640	**.043**	.150
Depth of sleep (5-35)	18.9 ±3.6	20.2 ±4.9	.365	15.9 ±5.2	17.0 ±4.6	.218	.290	.175
Sleep diary								
Length of sleep [hr]	7.1 ±1.0	7.1 ±1.0	.697	7.6 ±1.6	7.6 ±1.3	.833	.306	.431
Latency [mn]	60.8 ±34.0	43.1±22.3	.114	30 ±41.5	30.1 ±38.9	.981	.060	.508
Awakenings [n]	0.6 ±0.8	0.3 ±0.6	.141	0.5 ±0.6	0.4 ±0.6	.596	.900	.701
Sleep efficiency [%]	87.3 ±7.8	90.2 ±4.0	.151	92.6 ±9.5	92.9 ±8.0	.882	.161	.496

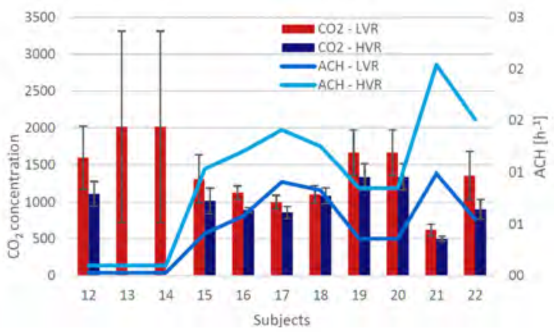

Figure 3: Average CO_2-concentration [ppm] and ACH [h^{-1}] in the bedroom of each subject of Location B.

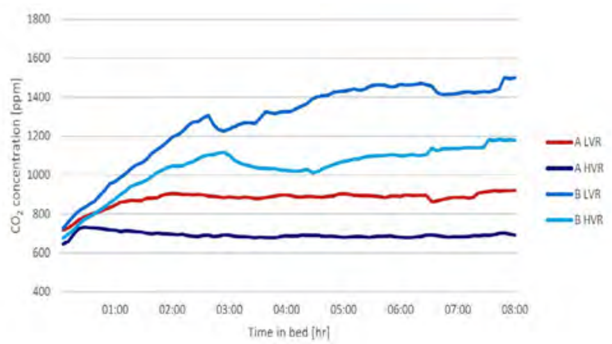

Figure 4: Average CO_2-concentration [ppm] measured during the second night for all bedrooms.

Concerning noise levels, Location A had an average sound pressure level of 35 dB when ventilation was at its low setting (range 31 dB to 37 dB). At a high ventilation rate, the average was 39 dB, ranging from 34 dB to 48 dB. This difference was significant. For Location B similar significant differences in noise levels were measured (Table 3).

The actigraph data of the Sensewear armband was analyzed in terms of lying down, length of sleep, latency, awakenings, efficiency and the depth of the sleep (Table 4). Time spent sleeping (assessed from the Sensewear data) were not significantly different for both ventilation settings. This applies to both locations. The sleep efficiency was significantly different for Location B only, with a lower efficiency at a high ventilation rate. The length of sleep and the latency show a significant difference between Location A and Location B.

Questionnaires

Table 5 shows the results that are obtained from the questionnaires for assessing the perceived IAQ (HOPE) and the sleep quality (PSQI, GSQS and sleep diary). The perceived IAQ indicates a significant difference for Location B. Subjects considered a better indoor air quality with the high ventilation rate. The subjects of Location A considered the air fresher with a high ventilation rate (HVR) but experienced more draught in the bedroom.

Correlations

Indoor environment parameters and building characteristics

Figure 5 shows that noise levels are in the same order of magnitude for both locations, while the realized ACH by the ventilation system differs (40 dB refers to the maximum value according to the Dutch building decree). Table 6 and 7 show the correlation coefficients (r) and the p-values of the measured indoor environment parameters (temperature, RH, CO_2 and noise) and the building characteristics for Location A and Location B respectively.

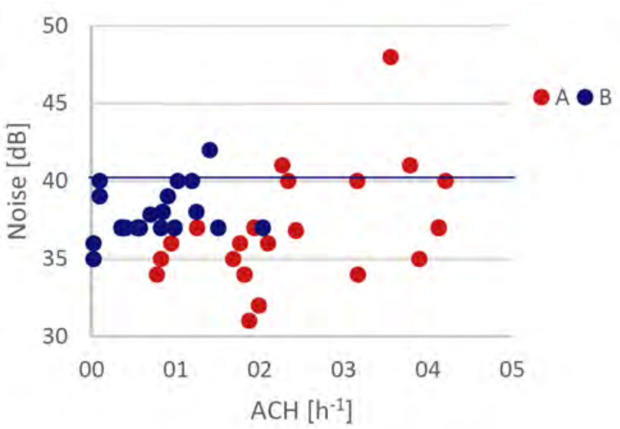

Figure 5: Relation sound pressure level (Noise) and Air Change per Hour (ACH) for Location A and Location B.

Table 6: Correlations between measured indoor environment parameters, building types, and subject characteristics for Location A.

	Volume bedroom *r (p-value)*	ACH *r (p-value)*	Persons in bedroom *r (p-value)*
Temp	-.24 (.312)	-.09 (.723)	-.16 (.506)
RH	-.04 (.850)	-.20 (.382)	**.60 (.003)**
CO_2	.38 (.084)	**-.49 (.022)**	**.55 (.009)**
Noise	.18 (.412)	**.46 (.031)**	-.05 (.813)

Table 7: Correlations between measured indoor environment parameters, building types, and subject characteristics for Location B.

	Volume bedroom *r (p-value)*	ACH *r (p-value)*	Persons in bedroom *r (p-value)*
Temp	-.33 (.160)	-.24 (.311)	.10 (.689)
RH	-.21 (.385)	**-.74 (.001)**	.20 (.407)
CO_2	**-.42 (.067)**	**-.81 (.001)**	**.65 (.002)**
Noise	-.32 (.141)	.32 (.151)	-.17 (.439)

Table 8: Correlations [r (p-value)] between the indoor environment parameters (noise, temperature, RH, CO_2) and the subjective sleep quality results for Location A.

	Noise	Temp	RH	CO_2
Depth of sleep	.24 (.304)	.08 (.757)	.11 (.637)	.05 (.838)
Sleep quality	.25 (.257)	.11 (.659)	.17 (.446)	.02 (.923)
Length of sleep	-.23 (.326)	**-.30** (.214)	.20 (.379)	**.31** (.179)
Latency	**-.33** (.141)	**.62 (.004)**	-.15 (.515)	-.26 (.247)
Awakenings	-.23 (.335)	**.64 (.004)**	-.18 (.456)	**-.42** (.068)
Efficiency	.19 (.414)	**-.69 (.001)**	.24 (.293)	**.36** (.106)
PSQI	.10 (.666)	.28 (.252)	.12 (.612)	-.29 (.199)
GSQS	.05 (.826)	**.42** (.067)	-.03 (.891)	.01 (.990)

Indoor environment parameters and subjective sleep quality results

The correlation between the indoor environment parameters and the subjective sleep quality results are shown in Table 8 for Location A and in Table 9 for Location B. For Location A, a correlation was observed between the temperature and sleep latency, and between the temperature and the number of awakenings and with the efficiency. The CO_2 concentration correlates with the length of sleep for Location B.

Table 9: Correlations [r (p-value)] between the indoor environment parameters (noise, temperature, RH, CO_2) and the subjective sleep quality results for Location B.

	Noise	Temp	RH	CO_2
Depth of sleep	-.02 (.931)	.18 (.453)	.26 (.275)	-.25 (.285)
Sleep quality	.14 (.545)	.13 (.585)	.27 (.256)	.15 (.520)
Length of sleep	-.19 (.393)	-.03 (.910)	.19 (.425)	**.57 (.009)**
Latency	.15 (.503)	**-.40** (.078)	-.09 (.710)	**-.35** (.131)
Awakenings	-.27 (.218)	.28 (.237)	.21 (.371)	**.32** (.175)
Efficiency	-.13 (.552)	**.38** (.099)	.09 (.722)	**.36** (.117)
PSQI	.05 (.821)	-.14 (.566)	-.22 (.343)	.10 (.676)
GSQS	-.14 (.539)	.02 (.924)	-.20 (.402)	.10 (.666)

Table 10: Correlations [r [p-value]) between the objective and subjective measured indoor environment parameters.

Location A	Noise	Temp	RH	CO_2
HOPE	**.31** (.180)	**.46** (.057)	**-.33** (.151)	**-.38** (.096)
Temp	**.36** (.121)	**.44** (.065)	**-.40** (.078)	**-.43** (.060)
IAQ	.07 (.760)	**.44** (.070)	-.26 (.260)	**-.33** (.154)
Location B	**Noise**	**Temp**	**RH**	**CO_2**
HOPE	-.25 (.264)	.24 (.308)	.22 (.358)	.08 (.725)
Temp	-.01 (.970)	.20 (.390)	.11 (.649)	-.21 (.367)
IAQ	**-.39 (.077)**	.23 (.331)	**.34 (.145)**	**.36 (.122)**

Correlation between objective and subjective results

The sleep quality was measured both objectively (derived from data by Sensewear) and subjectively (by questionnaires). The results of both input only showed a correlation for the length of sleep ($r > .3$, $p < .05$). This was for both locations. Table 10 presents the correlation outcomes for the measured indoor environment parameters and the subjective information from the HOPE questionnaire (complete and only questions specifically related to temperature and IAQ). No significant correlations were observed.

Table 11: Differences in rating between men and women describing indoor environmental quality and sleep quality.

	Men n = 10	Women n = 12	Difference *p*-value
Bedroom measurement			
Temperature [°C]	19.4 ±0.8	18.9 ±0.8	.092
Questionnaires			
Hope (total) (10-66)	22.65 ±7.7	32.2 ±5.6	**.003**
Temperature (1-28)	9.7 ±4.1	13.5 ±3.1	**.032**
IAQ (1-28)	11.1 ±3.01	16.1 ±3.6	**< .001**
Sleep diary			
Length of sleep [hr]	6.9 ±1.3	7.7 ±1.1	.057
Awakenings [n]	0.3 ±0.5	0.6 ±0.8	.054

Table 12: Differences between older (55 years and older) and younger (under 55 years) subjects

	< 55 year n = 10	> 55 year n = 12	Difference *p*-value
Sleep diary			
Depth of sleep (5-35)	20.0 ±2.9	15.6 ±5.6	**.019**
Awakenings [n]	0.3 ±0.5	0.6 ±0.8	**.003**

Gender

The results of both the objective and subjective measured indoor air quality and sleep quality have been analyzed further for differences between men and women. That comparison is shown in Table 11. The length of sleep and awakenings did not show a difference between men and women. However, the HOPE questionnaire showed that temperature perception (men 9.7 vs women 13.5) and perception of the indoor air quality in the bedroom (men 11.1 vs women 16.1) were rated significantly more negative by women. Meanwhile, the objective bedroom temperature was not significantly different.

Age

Next, the participants have been divided into age groups of over 55 years and younger than 55 years (Table 12). The results of the sleep diary (subjective) show a significant difference between the groups. The number of awakenings is significantly higher in the group of older subjects ($p = .003$). Also, the depth of sleep is significantly lower in the age group of >55 years ($p = .019$).

DISCUSSION

This intervention study aimed to examine the relation between the indoor air quality and the sleep quality of ageing adults. It did so by creating two IAQ-conditions with a high and low CO_2 concentration. These conditions were obtained via a MVHR system set at a low or high ventilation rate. The subjects were investigated in their normal bedroom environment. The effect of a high ventilation rate (low CO_2 concentration), as compared to a low ventilation rate (high CO_2 concentration), was shown to be significant at both location A and B. However, CO_2 concentrations were higher in general at Location B. This was due to the overall lower ventilation rate provided by the systems at that location.

Only when the MVHR system was run at the low ventilation rate at Location B the CO_2 concentration was higher than aimed for in the Dutch building decree (around 1200 ppm). The temperature and RH conditions were within the range for comfortable and healthy dwellings from NEN 15251 (NEN, 2007).

The measured bedroom noise level was significantly higher (3 dB on average; $p = .003$) at the high ventilation rate at both locations. This higher sound pressure level, however, did not result in significant correlations with sleep quality indicators as measured. Notably, the measured sound pressure level was not different between the two locations at the high ventilation rate (both 39 dB), despite the fact that the ventilation rate for Location A was nearly three times higher (see Table 1 and Figure 5). This finding highlights the effect of design characteristics of MVHR systems.

Subjects

The study was able to include middle aged subjects, though the number of participants originally aimed for was higher. Less than 10% of the persons invited decided to participate in the study. It is unclear what the cause for this low response rate is. Maybe people are hesitant to allow measurements in their bedroom, but this has to be confirmed in a future study.

Both women and men participated in the present study. The results show that they judged differently about the indoor environment. Women expressed more dissatisfaction. They rated the indoor environmental quality (HOPE questionnaire, range 10-66) at 32 points, versus 23 points by men, a significant difference. More dissatisfaction by women was also reported in the study of Hwang et al. (Hwang, Lin, & Kuo, 2006).

When studying the sleep quality, the age of the subjects should be considered. While adults sleep 7 to 8 hours, people above 60 years of age tend to sleep only 6.5 hours per night (Eekhof & Scherptong-Engbers, 2016). Also sleep characteristics appear to change at higher age; the depth of sleep fluctuates faster, the duration of the REM-sleep reduces, and the frequency of nightly awakenings increases (Carskadon, Van den Hoed, & Dement, 1980). The results of this study confirm these findings. A significant difference in the subjectively measured depth of sleep (reduced) and number of awakenings (increase) was observed for the participants older than 55 years.

On-body measurements

The on-body measurements, as obtained with the use of actigraphy (Sensewear armband), did not reveal significant differences in sleep quality for the two ventilation settings at both locations.

However, sleep quality appeared to be different between the two locations. The length of sleep was longer at Location B (6.8 hrs) when compared to Location A (5.8 hrs) (p = .045), while latency was shorter, The number of awakenings was also higher, though not significant, at Location B (7.0) versus Location A (5.1). These outcomes may be related to the higher average age (55 year vs 45 year) of participants at Location B. This aligns with the outcome of Eekhof & Scherptong-Engbers, 2016.

Questionnaires

The outcomes from the applied questionnaires did not reveal significant differences between a situation at low versus high CO_2 concentration level at either location. This was also observed in the studies of Chenxi, Strøm-Tejsen and Mishra. The only difference was observed in the perception of the indoor air quality. The higher ventilation rate (lower CO_2 level) was judged better overall. The subjects perceived, more fresh air.

There were no significant correlations found between the perceived sleep quality and the CO_2 concentration. Only for Location B a significant correlation was identified with the length of sleep. It increases when the CO_2 level increases. Although there is a correlation noted, causality may be disputed as length of sleep is also dependent on the lifestyle of the subject.

When comparing the on-body measurement and the questionnaires, the length of sleep and the latency to sleep were showing the same tendency (moderate correlation). In contrast, the number of awakenings was very different. The Sensewear appeared to detect about 10 times more awakenings than were noted by the subjects in their sleep diary. These results point at the direction that it should be possible to use only one questionnaire to measure the sleep quality, in addition to the Sensewear. This is in line with the suggestion of (Mishra, van Ruitenbeek, Loomans, & Kort, 2018).

Limitations

The inclusion of less than 10% from a total of 275 households may result in a group of subjects not representative for the overall population. It might be useful in a future study to ask those people who decided not to participate for their reasons not to do so. Also, the reduction of the study load by limiting the number of measurement days may be helpful to increase the participation rate. The current outcomes suggest that more participants are required to confirm the current results and potentially find other significant results.

The fact that the difference in CO_2 concentration obtained for the two settings of the ventilation system may be regarded limited, will have affected the outcomes. This is amongst others reflected in the limited number of significant outcomes, apart from the fact that the number of participants is limited. However, the apartments that were part of the research presented a realistic situation and therefore may be regarded representative for the case investigated, i.e. with the use of MVHR systems.

Questionnaires appeared to be difficult to handle for some of the participants and in a few cases, several days might have been filled in at one day. Reducing the number of questionnaires and relying on data as provided by actigraphy may be helpful to reduce this problem. (Carskadon, Van den Hoed, & Dement, 1980)

(Craskadon & Dement, 2011). The results from this research indicate that options for that appear valid.

Recommendations

Sleep quality is not only important for well-being but can also influence the next-day performance. A study of Strøm-Tejsen shows that when air quality was improved the subjects felt better the next day, they were less sleepy and more able to concentrate. Also, the performance of a test of logical thinking improved (Strøm-Tejsen, Zukowska, Wargocki, & Wyon, 2016). It would be interesting to add the next day performance analysis in future research.

Apart from the bedroom environment, sleep quality can be affected by other factors, like work stress, psychological factors, financial worries, and anxiety (Grandner & Pigeon, 2013). These factors were not evaluated in the present study, but it may be worthwhile to include them in future investigations.

Sound pressure level was measured in the bedrooms and was shown to increase at a high ventilation rate by ca. 3 dB. Certainly when using mechanical ventilation systems, the questionnaire should include an explicit question that judges noise, for comparison.

Practical implementation

The use of a mechanical ventilation system with heat recovery (MVHR) was essential in the present study because it allows controlling the bedroom environment. However, the MVHR systems appeared to perform differently at the investigated locations. The ventilation rate was significantly higher at Location A (low 42 m^3/h; high 91 m^3/h) when compared to Location B (low 15 m^3/h; high 31 m^3/h). This of course affected the IAQ-metrics. The measured sound pressure level at a high ventilation rate (39 dB ±3.7) was similar at both locations. Performance characteristics therefore should not be limited to the flow rate when selecting a MVHR system. It may affect sleep quality, and may incite people to lower the ventilation rate.

During the intake, it was observed that several filters of MVHR systems were not replaced on time. Also, most of the subjects normally were only using the lowest ventilation rate level of the system and four of the subjects at Location B had turned off the air supply permanently, because of draught and noise. Apparently, there is a lack of knowledge with regards to the ventilation system among the participants. To assure a properly working system, occupants must be informed better about the ventilation system (functioning, use, maintenance). The COVID-19 experience provides a further incentive for that.

CONCLUSION

The present study aimed to examine if there is a relation between the indoor air quality, indicated by CO_2 concentration, and the sleep quality of ageing adults. The change in CO_2 concentration has been realized by changing the ventilation rate with a MVHR system. No significant effects were identified between the CO_2 concentration and the objectively measured sleep quality via actigraphy, as well as the information from the questionnaires. The subjects did report the bedroom air to be significantly fresher with a lower CO_2 concentration (high ventilation rate).

Characteristics of the subjects appeared to have a significant effect on sleep conditions (age) and on indoor air quality perception (gender). As the group of participants in this study was limited it is advised to repeat the study to enlarge the body of data to arrive at more statistically significant outcomes. The study, furthermore, identifies options to reduce the load on the participants in the data gathering of the sleep quality.

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