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MASTER

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

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Award date:
2020

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

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MASTER THESIS

Date
March 12, 2020

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Summary

The present study examined the effect of the indoor air quality, indicated by CO_2 levels, on sleep quality of ageing adults. Bedroom indoor air quality was changed by increasing ventilation rate with a MVHR system with the intention to decrease the CO_2 levels.

Twenty-two volunteers were studied during four consecutive nights in their bedroom at two different settings of the mechanical ventilation with heat recovery (high and low). During the night indoor air quality was measured continuously (CO_2, temperature, and relative humidity), additionally the background noise was measured. On body indices of sleep quality were analyzed using actigraphy (Sensewear). Three different questionnaires (PSQI, GSQS and sleep diary) provided subjective data on sleep quality and the Hope questionnaire provided subjective data on the perception of indoor air quality.

Bedroom CO_2 increased rapidly during the night at a low ventilation rate (15 m^3/h) to 1409 ±412 ppm, but remained low at the high ventilation rate of 91 m^3/h (680 ±106 ppm CO_2). At the same time air humidity decreased at the high ventilation rate. The sound pressure level remained low at the low ventilation rate (35 ±2 dB) but increased to 39 (±4) dB at the high ventilation rate. The bedroom air temperature remained stable and did not differ significantly between the conditions.

The sleep quality obtained with the Sensewear was not affected by the change in IAQ. No significant difference was also analyzed for the PSQI and the GSQS questionnaire. However, the HOPE questionnaire (indoor air quality) had multiple significant correlations with the measured indoor environmental quality (IEQ). The subjects rated the air fresher but experienced more air draft with the high ventilation rate. The results of the sleep diary (length of sleep and latency) were correlated with the results obtained with the Sensewear.

Characteristics of the subjects appeared to have a significantly effect on sleep conditions (age) and on indoor air quality perception (gender). Older people experienced more nightly awakenings, and the depth of sleep was significantly better. Women judged the air quality significantly lower if compared to men.

Samenvatting

De huidige studie onderzocht het effect van de binnenluchtkwaliteit, met name CO_2-niveaus, op de slaapkwaliteit van oudere volwassenen. De kwaliteit van de binnenlucht in de slaapkamer werd gewijzigd door de ventilatiecapaciteit te verhogen middels een warmteterugwinning(WTW)-systeem, met de bedoeling het CO_2-niveau te verlagen.

Tweeëntwintig vrijwilligers werden gedurende vier opeenvolgende nachten in hun slaapkamer onderzocht tijdens twee verschillende ventilatiestanden van het WTW-systeem (hoog en laag). Gedurende de nacht werd de binnenluchtkwaliteit constant gemeten (CO_2, temperatuur en relatieve vochtigheid), en tevens werd het achtergrondgeluid gemeten. De slaapkwaliteit werd geanalyseerd met behulp van de data verkregen middels een Sensewear armband die de deelnemers gedurende de nacht om hun arm droegen. Drie verschillende vragenlijsten (PSQI, GSQS en slaap dagboek) gaven subjectieve gegevens over de slaapkwaliteit en de Hope-vragenlijst leverde subjectieve gegevens over de perceptie van de binnenluchtkwaliteit.

De CO_2 concentratie in de slaapkamer nam 's nachts snel toe bij een lage ventilatiecapaciteit (15 m^3/uur) tot 1409 ± 412 ppm, maar bleef laag bij de hoge ventilatiecapaciteit van 91 m^3/uur (680 ± 106 ppm CO_2). Tegelijkertijd nam de luchtvochtigheid af bij een hoge ventilatiecapaciteit. Het geluidsdrukniveau bleef laag bij een lage ventilatiecapaciteit (35 ± 2 dB), maar nam toe tot 39 (± 4) dB bij de hoge stand. De luchttemperatuur in de slaapkamer bleef stabiel en verschilde niet significant tussen de ventilatiestanden.

De slaapkwaliteit verkregen met de Sensewear werd niet beïnvloed door de verandering in binnenluchtkwaliteit. Er werd ook geen significant verschil geanalyseerd voor de PSQI en de GSQS-vragenlijst. De HOPE-vragenlijst (binnenluchtkwaliteit) had echter meerdere significante correlaties met de gemeten binnenluchkwaliteit. De proefpersonen beoordeelden de lucht frisser, maar ondervonden meer tocht met de hoge ventilatiecapaciteiten. Tussen de resultaten van het slaapdagboek (slaapduur en slaap latentie) en de resultaten verkregen met de Sensewear is een correlatie gevonden.

De kenmerken van de deelnemers bleken een significant effect te hebben op de slaap (leeftijd) en de perceptie van de binnenluchtkwaliteit (geslacht). Ouderen hadden meer wakker momenten in de nacht en de diepte van de slaap was aanmerkelijk beter. Vrouwen beoordeelden de luchtkwaliteit significant lager dan mannen.

Abbreviations

ACH	Air Change per Hour
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
MVHR system	Mechanical Ventilation with Heat Recovery
LVR	Low Ventilation Rate
HVR	High Ventilation Rate
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
HOPE	Health Optimisation Protocol for Energy Efficient Buildings
PSQI	Pittsburg Sleep Questionnaire Index
GSQS	Groningen Sleep Questionnaire Scale
EPC	Energy Performance Coefficient

Symbols

CO_2	[ppm]	Carbon Dioxide Concentration
RH	[%]	Relative Humidity
A	[m^2]	Floor area
V	[m^3]	Bedroom volume
dB		Decibel

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1. Introduction

The European directive EPBD (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 requirements in the design of buildings at present and in the future.

Improved insulation of newly built dwellings and insulation during renovation of old dwellings significantly reduces heat loss. As a result of improved insulation, the contribution of air infiltration to the Indoor Air Quality (IAQ) is reduced and the ventilation system becomes more and more responsible for the indoor air quality.

1.1. Indoor Air Quality

Poor ventilation can lead to a high indoor carbon dioxide (CO_2) concentration, which generally is used as the proxy for assessing Indoor Air Quality (IAQ). The ASHRAE standard recommends a stable concentration level of CO_2 at 700 parts per million [ppm] above outdoor levels, with an outdoor level of 400 ppm, 1100 ppm is acceptable for indoors. Regarding the Dutch Building Standards, the regulations require a minimum of 25 m^3/h per person, which is based on an acceptable CO_2 concentration of 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. With an outdoor level op 400 ppm, a CO_2 concentration of 900 ppm for newly and renovated buildings and a CO_2 concentration of 1200 ppm for existing buildings is recommended (NEN, 2007).

Insufficient ventilation, and therefore a high CO_2 concentration, can have a negative effect on health. Higher ventilation rates are associated with a lower prevalence of building-related health problems, fewer respiratory symptoms and reduced symptoms of asthma (Sundell, 2011). CO_2 levels of 800 ppm for healthy adult and a level of 600 ppm for people with health complains are to be strived for to prevent health problems (Roelofsen, 2012). Investigations in homes with MVHR systems showed that higher ventilation rates were associated with fewer health problems (Jongeneel, Bogers, & van Kamp, 2011).

1.2. Ventilation in dwellings

To reduce costs and energy losses, and to obtain a good indoor air quality, the type of ventilation system is determinative. Nevertheless, the ventilation accounts for a significant part of total heat loss. Therefore, over the past few years many homes in The Netherlands have been equipped with a balanced mechanical ventilation system with heat recovery (MVHR) (Jongeneel, Bogers, & van Kamp, 2011).
Ventilation is necessary to provide people in a home with fresh air and the ventilation rate is responsible to control the indoor air quality in a room at a level that creates a pleasant and healthy environment.

A MVHR-system extracts the air from potentially polluted locations (kitchen, bathroom, toilet and utility rooms) and supplies fresh air to the living rooms and bedrooms. The extracted air is removed through a central heat exchanger, to recover heat and provide that to the supply air (Figure 1-1).

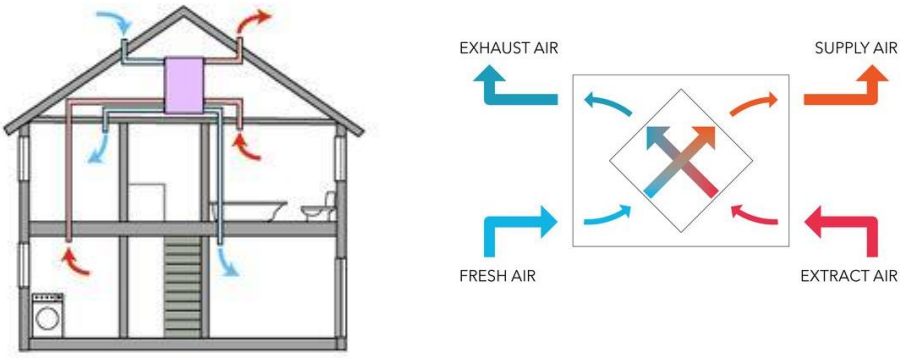


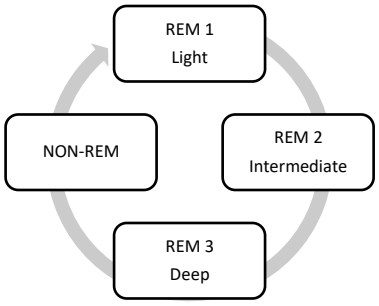
Figure 1-1: MVHR system in a dwelling (figures: www.pasivehouseschool.nl).

Unfortunately, experiences with this system are not always positive. Research has shown that many occupants of houses in The Netherlands equipped with MVHR systems are bothered by noise, draught, heat and poor indoor air quality. They also complain about lack of personal control over the ventilation system (Duijm, 2006). Balvers et al. concluded that the Dutch houses with MVHR system have a variety of shortcomings, such as: insufficient ventilation capacity, noise, no operable windows, no bypass, unclean ventilation system, incorrect design, incorrect use and insufficient maintenance (Balvers, et al., 2012).

1.3. Sleep

Sleep is essential for the body to recover from both physical and psychological fatigue as experienced throughout the day, and restore energy to maintain bodily functions (Opp, 2009). Sleep is comprised of two stages: rapid eye movement (REM) and non-REM (NREM) sleep. Subsequently, NREM sleep can be divided into 3 stages (Figure 1-2). These stages alternate cyclically across a sleep episode (Craskadon & Dement, 2011), usually four or five of them per night (Figure 1-3). Recent reports on sleep show that adults require 7-9 hours of sleep per night (Hirschkowitz, 2015). According to the work of Nan et al., sleep problems threaten health and quality of life for up to 45% of the world's population, and 35% of people feel that they do not get enough sleep, accompanied by a negative impact on health (Nan , Bin, & Yingxin, 2018). In general, the indoor environment, bed microclimate, psychological state, body condition and circadian rhythm can impact sleep. Compared with other factors that affect sleep quality, indoor environment is at present adjustable and controllable, making it possible to improve sleep.

Figure 1-2. Sleep cycle: REM 1 (light), REM 2 (Intermediate), REM 3 (Deep) and NON-REM.



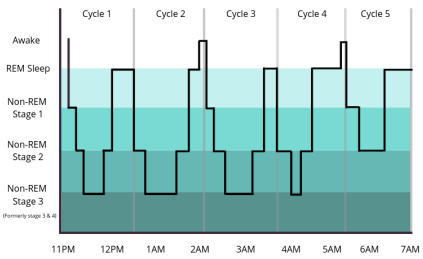


Figure 1-3: sleep cycles during the night.

1.4. Indoor environment & sleep quality

Indoor environment is determined by thermal environment, acoustic environment, lighting environment, and indoor air quality (IAQ) (Figure 1-4). These four aspects of indoor environments have different influences on sleep quality (Grandner & Pigeon, 2013).

The past two decades, studies examining the relationship between environment and sleep have mainly focused on the noise levels (acoustic environment) (Halperin, 2014) (Pirrera, Valck, & Cluydts, 2014), lighting environments and on the thermal environment (Lin & Deng, 2008) (Okamoto-Mizuno & Mizuno, 2012) (Lan, Lian, & Lin, 2016) (Pan, Lian, & Lan, 2012) (Fergus, 2019) but less on the indoor air quality (Strøm-Tejsen, Zukowska, Wargocki, & Wyon, 2016) (Mishra, van Ruitenbeek, Loomans, & Kort, 2018) (Liao & Laverge, 2019).

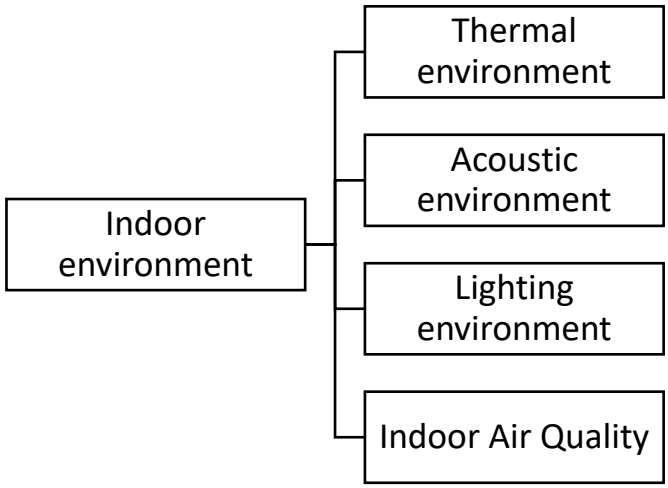


Figure 1-4: Indoor environment, is determined by thermal environment acoustic environment, lighting environment and indoor air quality.

Nan et al. concluded form the results of the online investigation in their research that noise and temperature are the most dissatisfying environmental factors during sleep, followed by humidity, light and IAQ (Nan , Bin, & Yingxin, 2018).

1.5. Indoor Air Quality & Sleep

Only few studies have focused on the effect of ventilation on the Indoor Air Quality in a bedroom and on the Sleep Quality of the person. 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).

Another study shows that reducing the CO_2 concentration through natural ventilation (660 ppm compared to 2585 ppm) and mechanical ventilation (835 ppm compared with 2395 ppm) leads to a clear improvement in sleep quality and the perceived freshness of the bedroom air (Strøm-Tejsen, Zukowska, Wargocki, & Wyon, 2016). This study also showed that reduced sleep quality due to insufficient ventilation has a

significant effect on the next day's performance; people felt more sleepy and harder to concentrate. Research in Belgian student rooms showed that residents fell asleep more easily, woke up more easily, and felt more rested when they slept with the window open instead of with the window closed, ie with relatively more fresh air supply (Laverge & Janssens, 2011). A more recent study, where the IAQ was changed by opening/closing a window (CO_2 concentration of 1656 ppm with 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). The results of the GSQS increased slightly (0.87 point) with the window open (lower CO_2 concentration), which means no improvement in sleep quality (Liao & Laverge, 2019).

1.6. Research scope

Recent studies regarding 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 the noise. In order to achieve a controlled ventilation rate and limit influence on the temperature and the noise from outside, a MVHR system was used in this study to influence the CO_2 levels. The studies from Mishra et.al., Liao et. al. and Strøm-Tejsen et.al. are conducted with students. However, the majority of our population are middle-aged men and women. Therefore, this study has included ageing adults leading an orderly life.

The aim of the present study was to examine if there is a relation between the indoor air quality, and the sleep quality of ageing adults. CO_2 is set as the proxy voor IAQ. The change in IAQ has been realized with a MVHR system, to create as constant conditions as possible.

Main question

How is indoor air quality (IAQ), indicated by CO_2 levels, related to sleep quality of ageing adults in a bedroom by applying a balanced mechanical ventilation system with heat recovery (MVHR)?

Sub-questions

- Are the subjective measurements (questionnaires) comparable to the objective measurements (Sensewear and logger)?
- Is there a relation between the objective and subjective measurements and the characteristics of the subjects, such as gender and age?

2. Method

2.1. Multiple case-controlled study

Sleep quality and Indoor Air Quality were studied in two different conditions (Figure 2-1). The first condition was with the mechanical ventilations system at a low ventilation rate (LVR), level 1, and the second condition was with the mechanical ventilation system at a high ventilation rate (HVR), level 3. The indoor air quality was assessed objectively via 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 (Sensewear Figure 2-4) armband and a Flex sensor (Figure 2-2). Actigraphy is a well-validated method for field studies of sleep (Kushida, et al., 2001). The perceived indoor air quality and the sleep quality were measured subjectively with the use of questionnaires.

Figure 2-1: Method of the research for two cases: 1. Low ventilation rate 2. High ventilation rate

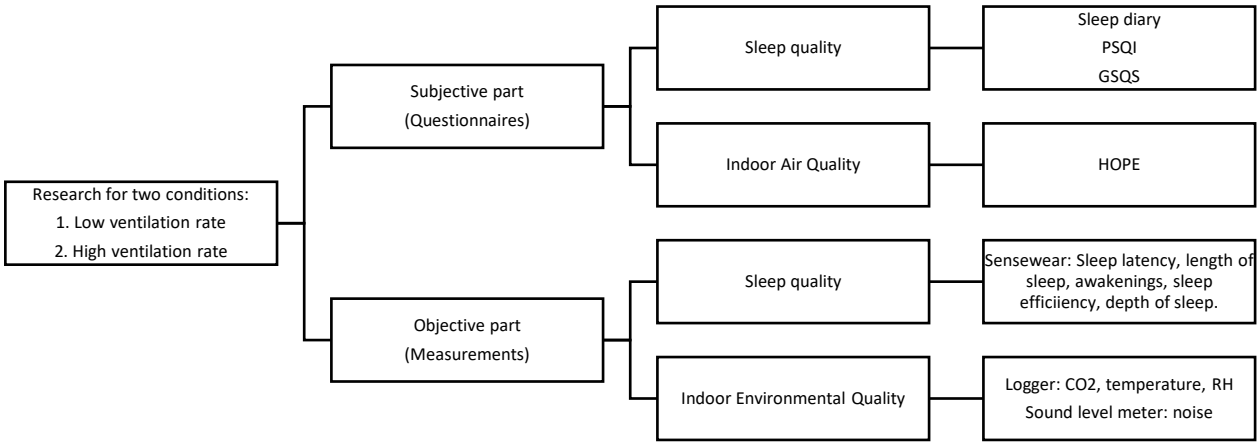


Figure 2-2: Sensewear armbands (Bodymedia) used for the objective measurements of the sleep quality.

Figure 2-3: Flexsensor (Antratek), used to detect restless behavior.

Figure 2-4: Flow finder used for the measurements of the ventilation rate (www.acin.nl).

The measurements were conducted during four consecutive nights (Monday until Friday) for both conditions: low ventilation rate (MVHR system on level 1) and high ventilation rate (MVHR system on level 3). The bedroom door and windows were closed during the night, but at daytime the subjects could close or open the window, and change the ventilation, according to their preferences. The ventilation rate for low and high ventilation was measured during the intake of the subject in the bedroom with the use of a flow finder (Figure 2-3).

Because of the restricted availability of equipment, and due to the duration of the recruitment of the participants, the measurements were performed in two groups. The measurements of the first group (location A) were in March and April 2019. The second group (location B) was studied from October until December 2019. The outdoor temperatures were comparable between both groups and not significantly different for both measurement conditions (p = .900 and p = .202), while the humidity was higher in the second group, location B (p = .038).

The measurements were conducted in the heating period (October until May), because normally the fresh air supply is lowest during these colder months especially because of limited use of operable windows and partly closed façade shutters.

2.2. Location

Subjects who volunteered for this study all lived in an apartment. The characteristics of the buildings differed from each other (Table 2-1), but all apartments were equipped with a comparable MVHR system.

2.2.1. Location A

For the first measurements, conducted in March 2019, twelve participants were recruited, who all live in the same building (location A). The complex was built in 1920 and located in Amsterdam. Between 2015 and 2018 it was radically renovated. The façade was insulated, all the windows were renewed, and the interior was totally stripped to meet the comfort standards. New walls and floor heating were installed. The heating and ventilation have been renewed to meet low energy requirements.

Building characteristics of the different apartments are comparable. However, the orientation, location in the building (top floor, ground floor etc) and volume of the bedrooms differ from each other.

2.2.2. Location B

The second group was studied from October until December 2019. The participants all live in the region of Utrecht. Thirteen participants were recruited, spread over four locations (B1- B4). The characteristics of the buildings differ from each other (Table 2-1).

Table 2-1: Characteristics of the buildings of the subjects.

	Location A	Location B			
		B1	B2	B3	B4
Year of construction	1920	1966	1962	2001	2019
Year of renovation	2018	-	2016	-	-
Type of heating	Floor heating	Radiator	Radiator	Radiator	Floor heating
Type of ventilation	MVHR system	MVHR system	MVHR system	MVHR system	MVHR system
City	Amsterdam	De Bilt	De Bilt	De Bilt	Utrecht
Energy requirements	Energy label A		Zero Energy building		EPC 0

2.3. Subjects

In total 275 people were approached at two different locations. The locations were selected because all apartments were recently renovated and could therefore meet the requirements of the study. Detailed characteristics of the people living in the apartments were not available at the start of the study.

All people received a written request to participate, and upon their positive response, they had an intake by telephone. Finally, inclusion of the volunteers was completed after a personal intake (Figure 2-5).

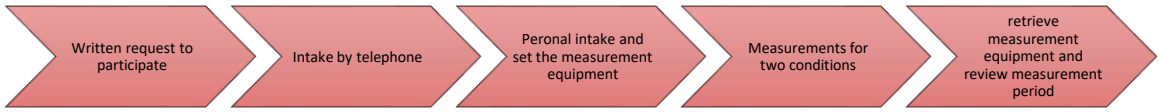


Figure 2-5: Process for the participants.

Twenty-five subjects participated in the research (Table 2-2), spread over two locations. In total 11 male volunteers and 14 female volunteers were included. The mean age of the subjects was 50 years (standard deviation 18.9 year). Six of the participants shared one bedroom, and two other participants slept with 2 persons, but only one person participated in the study.

Table 2-2: Characteristics of the subjects and the bedroom.

	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

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, as studies have shown that alcohol can affect sleep (Singleton & Wolfson, 2009).

2.4. Ventilation system

All the apartments have an individual mechanical ventilation system with heat recovery (MVHR) (Figure 2-7). The bedroom has one air inlet (Figure 2-7). To control ventilation rate, the kitchen or bathroom has a switch to change the system to a different level: minimal (only for group A) or 1, 2 and 3 (Figure 2-6). The ventilation rate at these levels (Table 2-3), differs between the low and high ventilation rate (p = <.001) and differs between the apartments because it depends on the volume of the rooms.

Figure 2-6. Switch to change the level of the ventilation system.

Figure 2-7: Left: Picture of MVHR system on Location A. Middle: MVHR system on Location B. Up Right: Air inlet Location B2. Bottom right: air inlet location A, B1, B3 and B4.

Table 2-3: Ventilation rate [m³/h] and Air change per hour (ACH) for low ventilation and high ventilation on location A and location B.

	Location A			Location B		
	LVR	**HVR**	**Difference *p*-value**	**LVR**	**HVR**	**Difference *p*-value**
Ventilationrate [m^3/h]	41.6 ±14.1	91.5 ±25.1	**< .001**	15.2 ±11.5	30.8 ±22.8	**< .001**
ACH [h^{-1}]	1.5 ±0.5	3.3 ±0.8	**< .001**	0.5 ±0.3	1.0 ±0.6	**< .001**

Appendix A2 contains a list of the measured ventilation rate for each bedroom for the low and the high ventilation rate. The ventilation rate is compared with the regulations of the Dutch Building Standard, the requirements have not been met for all the apartments.

The switch to change the level of the ventilation system, contains an indicator light for the replacement of the filters of the MVHR system. This light burned red for seven of the eleven subjects of Location A.

2.5. Bedroom measurements

Both the indoor air quality and the sleep quality were objectively assessed through measurements in the bedroom of the participants.

2.5.1. Indoor environmental quality

The CO_2, temperature and relative humidity were measured during the nights with a sensor at a five-minute interval (Table 2-4). The sensors were placed about 1.5 meters from the subject's pillow to avoid participants breathing directly upon the sensors. The sound pressure level of the background noise was measured intermittently at two points, over ten seconds, with a sound level meter. The measurements were performed during the intake, mostly between 14:00 and 21:00. It was measured near the ventilation inlet and near the pillow at the height of the sleeping position.

2.5.2. Sleep quality

During the nights, the participants wore a Sensewear armband. This is a clinically tested and validated multi-sensor body monitoring system. It calculates activity level and the metabolism, from which the sleep latency, length of sleep, number of awakenings and the sleep efficiency can be derived. The Sensewear was worn on the right upper arm only at night. Additionally, a Flexsensor was used to observe the movement during the night. The Flexsensor measures the resistance at a five-minute interval, and the resistance increases when it is bend. The sensor was placed under the pillow of the participant, and when a peak appears in the data this was noted as restless behavior. Thereby, the number of times per night the participant showed restless behavior can be derived.

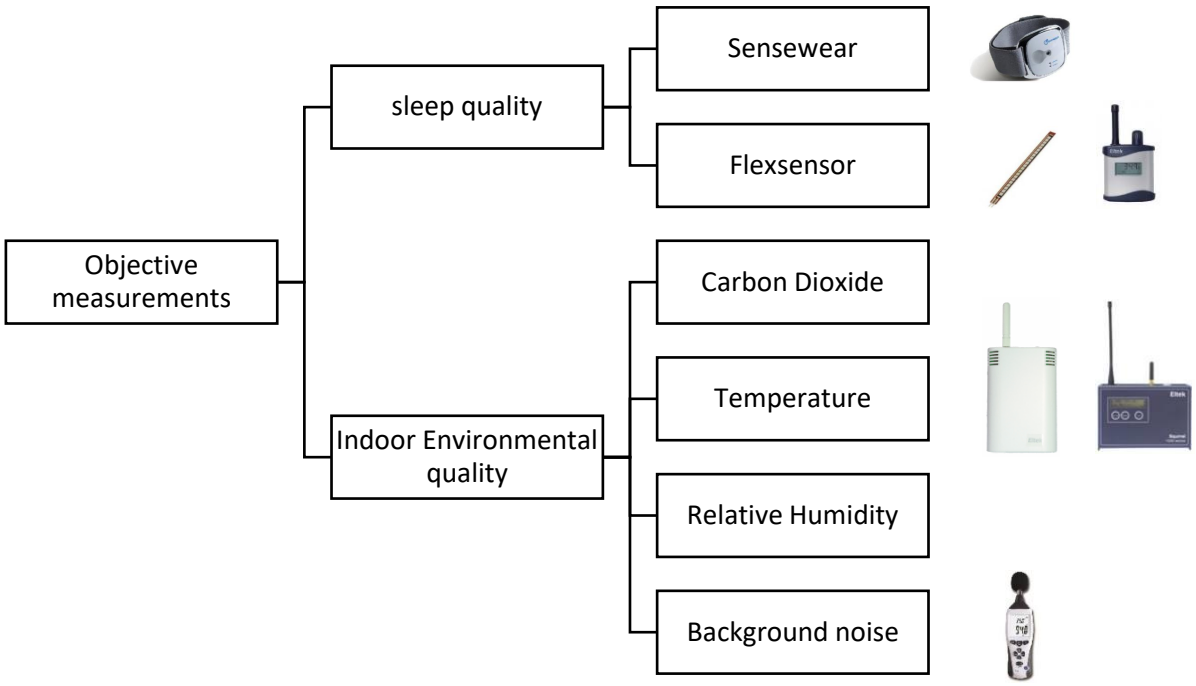


Figure 2-8: Objective part of the research with measurement equipment for the sleep quality and indoor air quality

Table 2-4: Specifications of the measurement equipment.

Measurement	Device	Variables	Range	Interval	Accuracy
Indoor Environmental Quality bedroom	Eltek Transmitter	CO_2 [ppm]	0 - 5000 ppm	5 min	± 50 ppm
		RH [%]	0 - 100 %	5 min	± 2 %
		T [°C]	5 - 45 °C	5 min	± 0.4 °C
	Data logger Grant squirrel				± 0.1
	Sound level meter	Decibel [dB]	0-100 dB	1 sec	± 1
Sleep Quality	Sensewear Armband (Bodymedia)	Sleep latency	min	1 min	± 2
		Length of sleep	min	1 min	± 2
		Awakenings	n	1 min	
		Sleep efficiency	0 – 100 %	1 min	
	Flex sensor (Antratek)	Number of peak/movements	-40 - 70 °C	5 min	± 0.4

2.6. Questionnaires

Questionnaires were used to measure subjectively the sleep quality and the indoor air quality.

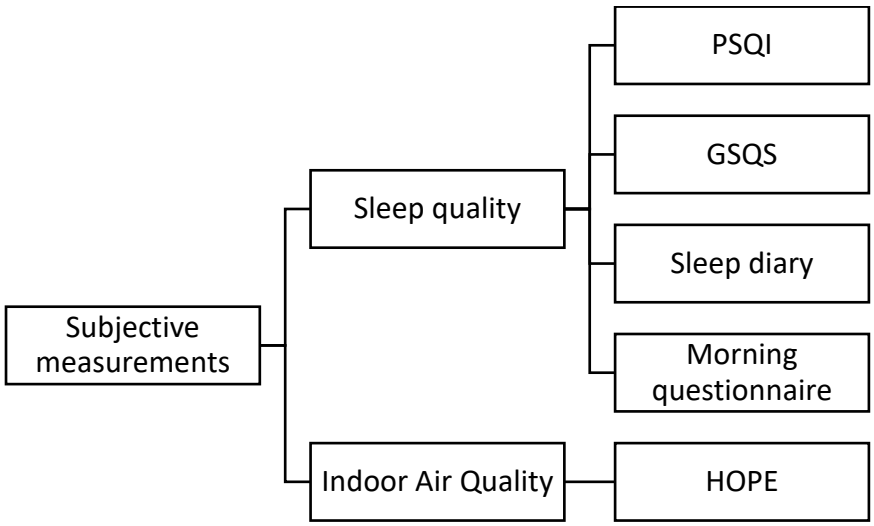


Figure 2-9: Subjective part of the research to measure the sleep quality and the indoor air quality.

2.6.1. Indoor Air Quality

The questionnaire to measure the IAQ is based on the validated list which was developed in the Health Optimization Protocol for Energy-Efficient Buildings (HOPE) Programme (Hope, 2001). The questions were filled in daily in the morning.

2.6.2. Sleep quality

The Pittsburgh Sleep Quality Index (PSQI) (Buysse, Reynolds, Monk, Berman, & Kupfer, 1988) rates sleep over longer periods of time (Table 2-5 and Appendix B). The ten questions of the PSQI were filled in before the experiment, after the first week of measuring in the first condition, and after the second week of measuring in the second condition.

The Groningen Sleep Quality Scale (GSQS), Table 2-5 and Appendix B, is a daily questionnaire with 15 true or false questions (Mulder, et al., 1980). A few questions of the Morning-questionnaires and the sleep diary were added to the GSQS questions. These questions were ratings of the depth of the sleep and restfulness during the night. 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 can be derived from the sleep diary. The sleep diary was filled in every morning.

Table 2-5: The questionnaires with the variables, range, interpretation and interval.

	Variables	Range	Interpretation	Interval
PSQI		0 - 21	0 = good 21 = bad	Weekly (3 times)
GSQI		0 - 14	0 = good 14 = bad	Daily
Morning questionnaire	Quality	1 - 7	1 = good, 7 = bad	Daily
	Depth	5 - 35	5 = very, 35 = not deep	Daily
Sleep diary	Sleep latency	Min		Daily
	Length of sleep	Hours		Daily
	Number of awakenings	N		Daily
	Sleep efficiency	0 – 100 %	0 = bad, 100 = good	Daily
HOPE	Total	10 – 66	10 = good, 66 = bad	Daily
	Temperature	1 - 28	1 = good, 28 = bad	Daily
	Indoor Air Quality	1 - 28	1 = good, 28 = bad	Daily

2.7. Data analysis

Excel was used for collection and preprocessing the data. The data from the Sensewear was processed in Bodymedia software 6.1 and 8.1 using weight and height together with information about age, sex and dominant arm. Both Excel and python were used for making graphs to investigate similarities and differences. The collected data was analyzed by the software IBM SPSS statistics 26 (statistical analysis). Only data for the period when the Sensewear armband indicated that the subjects were in bed was considered.

In the statistical analysis, first the normality was tested with the Shapiro-Wilk's test. Then it was determined if the measurement results for the two conditions (high or low ventilation rate) are significant different from each other. The Paired Sample T-test was used for normally distributed parameters, while Wilcoxon Signed-rank test was used for non-normal distributed data. Differences between parameters are established for $p < .05$.

To test for a correlation between the sleep quality and the indoor environmental quality the Pearson test was used. A distinction is made between the objective and subjective data. The strength of the relationship is expressed in different categories (Table 2-6), the strength of the correlation is weaker for a correlation related to subjective response (Kooi, 2017).

Table 2-6: The strength of the correlation for objective data and subjective data.

Objective data		**Subjective data**	
0.00-0.19	Very weak	0.00-0.19	Very weak
0.20-0.39	Weak	0.20-0.29	Weak
0.40-0.59	Moderate	0.30-0.49	Moderate
0.60-0.79	Strong	0.50-0.69	Strong
0.80-1.00	Very strong	0.70-1.00	Very strong

All the comparisons reported in the results are two-tailed with a significant *p*-value of .05.
Data are presented as mean values ± standard deviation.

3. Results

3.1. Subjects

In total 25 people participated in the project. However, data were included from only 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.

3.2. Outdoor conditions

The measurements were conducted in the heating period (October until May), because normally the fresh air supply is lowest during the colder months and use of windows in the apartment will be minimal in that case. Also, thermally less effect by increased outdoor temperature and solar radiation. The outdoor conditions during the measurement period (during the night when the subjects were in bed) are summarized in Table 3-1. At location A and at location B the temperature and RH were not significantly different between the low and high ventilation rate. Location A had an average temperature of 5.8 °C and an average relative humidity of 88% when the ventilation was low and an average temperature of 7.5 °C and an average relative humidity of 83% when ventilation was high. Location B had an average temperature of 6.2 °C and an average relative humidity of 91% when the ventilation was low and an average temperature of 5.8 °C and an average relative humidity of 91% when ventilation was high.

3.3. Locations

Because a significant difference was observed between the low and high ventilation rate (both $p < .001$) of location A and location B, and because the different measurement period (spring and autumn) resulted in other outdoor conditions, the two samples could not be regarded as one group. Therefore, Location A and Location B will be described and analyzed separately in the next chapters.

3.4. Bedroom measurements

3.4.1. Temperature

For location A, bedroom air temperatures averaged 19.2 °C with low ventilation and 19.4 °C with high ventilation (Table 3-1). For Location B, bedroom air temperatures averaged 19.1 °C with low ventilation and 18.9 °C with high ventilation. There were no significant differences in bedroom temperature between the conditions. Between location A and location B there was also no significant difference measured.

3.4.2. Relative humidity

For location A, the RH in the bedroom was 49% with low ventilation and 47% with high ventilation (Table 3-1). Location B had an average RH with low ventilation of 59% and with high ventilation of 53%. Bedroom RH was slightly lower in the higher ventilated bedroom, it has a significant difference for location A ($p = .016$), the outdoor RH was also significantly different for location A.

3.4.3. CO_2 concentration

Location A

The average CO_2 concentration was significantly lower at a high ventilation rate (680 vs 862 ppm), with a large individual variation of 486 to 1044 ppm at a low ventilation rate, and 429 to 825 ppm at a high ventilation rate (Table 3-2). This large individual variation is presented in Figure 3-1 for all 11 subjects of location A.

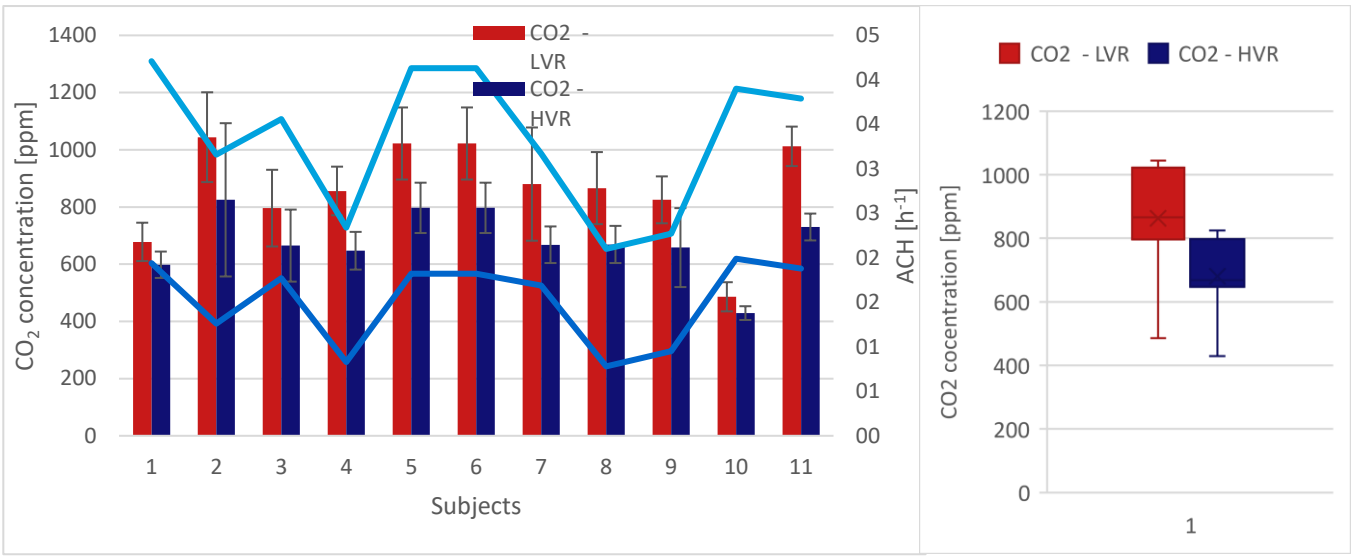


Figure 3-1: Left: Average CO_2 concentration [ppm] and ACH [h^{-1}] in the bedroom of each subject of location A with low or high ventilation rate. Right: Average CO_2 concentration of all subjects of location A.

Location B

The average CO_2 concentration was significantly lower at a high ventilation rate (1007 vs 1409 ppm), with a large individual variation of 625 to 2018 ppm at a low ventilation rate, and 505 to 1342 ppm at a high ventilation rate (Table 3-2). This large individual variation is presented in Figure 3-2 for all 11 subjects of location B.

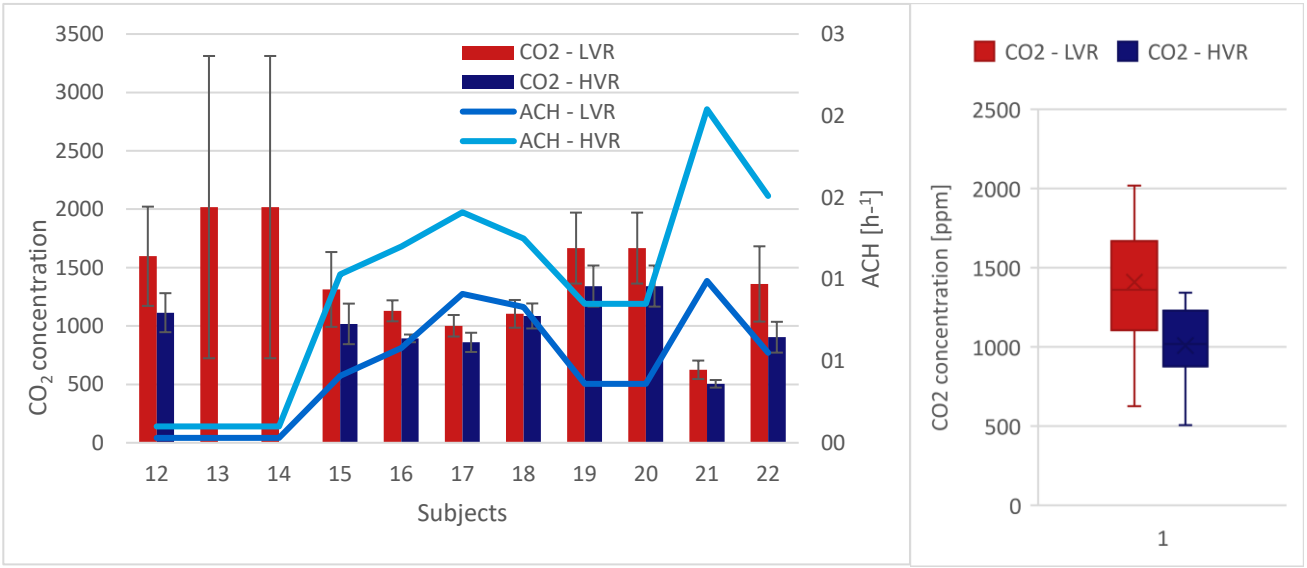


Figure 3-2: Left: Average CO_2 concentration [ppm] and ACH [h^{-1}] in the bedroom of each subject of location B with low or high ventilation rate. Right: Average CO_2 concentration of all subjects of location B.

While subjects were in bed, the CO_2 concentration remained rather constant, although a gradual increase during the first hour was observed in the bedrooms at a low ventilation rate (Figure 3-3). A graph of the measured CO_2 concentration per subjects for one night is included in appendix C.

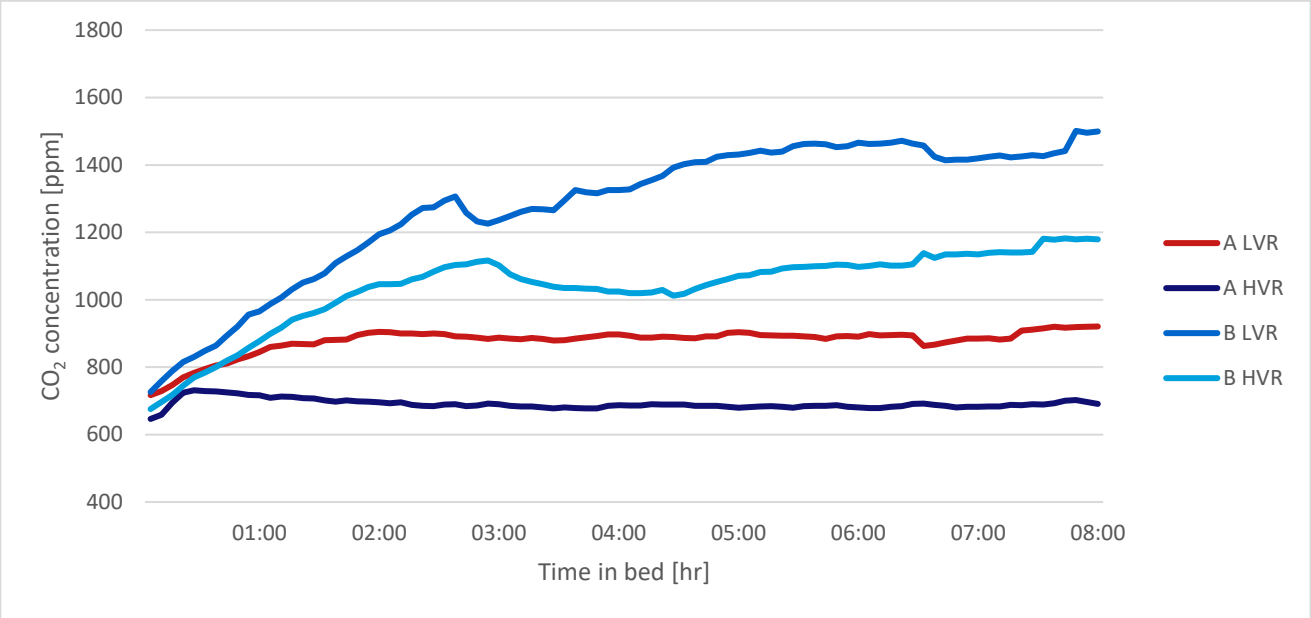


Figure 3-3: Average CO_2 concentration [ppm] measured during the second night for all bedrooms.

3.4.4. Noise

The bedroom noise was measured near the pillow, at the height of the sleeping position, of the subject (Table 3-1). Location A had an average noise level of 34.6 dB when ventilation was low, they ranged from 31 dB to 37 dB. For high ventilation it had an average of 39 dB and ranged from 34 dB to 48 dB. The bedroom noise was significantly different between the two conditions (p = .003).

The average value of noise for location B was 36.7 dB at low ventilation and ranged from 35 dB to 37 dB. An average of 38.9 dB was measured for high ventilation, and ranged from 37 dB to 42 dB. The bedroom noise was significantly different between the two conditions (p < .001).

Table 3-1: Outdoor conditions and average (and SD) temperature [°C], relative humidity [%], CO_2-concentration [ppm] and noise [dB] for each location and condition.

	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
Outdoor								
Temperature [°C]	5.8 ±0.14	7.5 ±2.54	**.04**	6.2 ±3.7	5.8 ±3.2	.739	.900	.202
RH [%]	88 ±10.7	83 ±9.9	**< .001**	91 ±1.3	91 ±2.3	.733	.643	**.038**
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

3.5. Sleep quality measurements

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 3-2).

Time spent sleeping under both conditions (assessed from de Sensewear data) were not significantly different for both locations. The sleep efficiency was only significantly different for location B, the efficiency is lower at a high ventilation rate. None of the other parameters showed a significant difference between the conditions. However, the length of sleep and the latency show a significantly difference between location A and location B.

Table 3-2: Average (and SD) of sleep quality for each location and condition, measured by the Sensewear.

	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
Sleep								
Stage 0 [%] *Awake*	22.7 ±11.5	19.23 ±8.7	.111	14.6 ±8.7	20.4 ±15.1	.054	.087	.428
Stage 1 [%] *light sleep*	49.2 ±13.3	49.4 ±9.5	.948	58.0 ±6.9	52.8 ±9.8	.195	.136	.351
Stage 2 [%] *deep sleep*	20.5 ±12.2	20.9 ±5.0	.920	20.5 ±7.3	20.4 ±8.0	.947	.919	.412
Stage 3 [%] *very deep sleep*	7.7 ±1.6	10.7 ±3.9	.197	7.1 ±1.7	6.4 ±3.6	.465	.529	.169

Sleep characteristics obtained by Sensewear and by Flexsensor show depth of sleep and simultaneously body movements. An example of both registrations is shown in Figure 3-4. These registrations were used to calculate the duration of each of four stages of sleep. No differences between location A and location B were observed, and there was no difference between the low and the high ventilation at both locations.

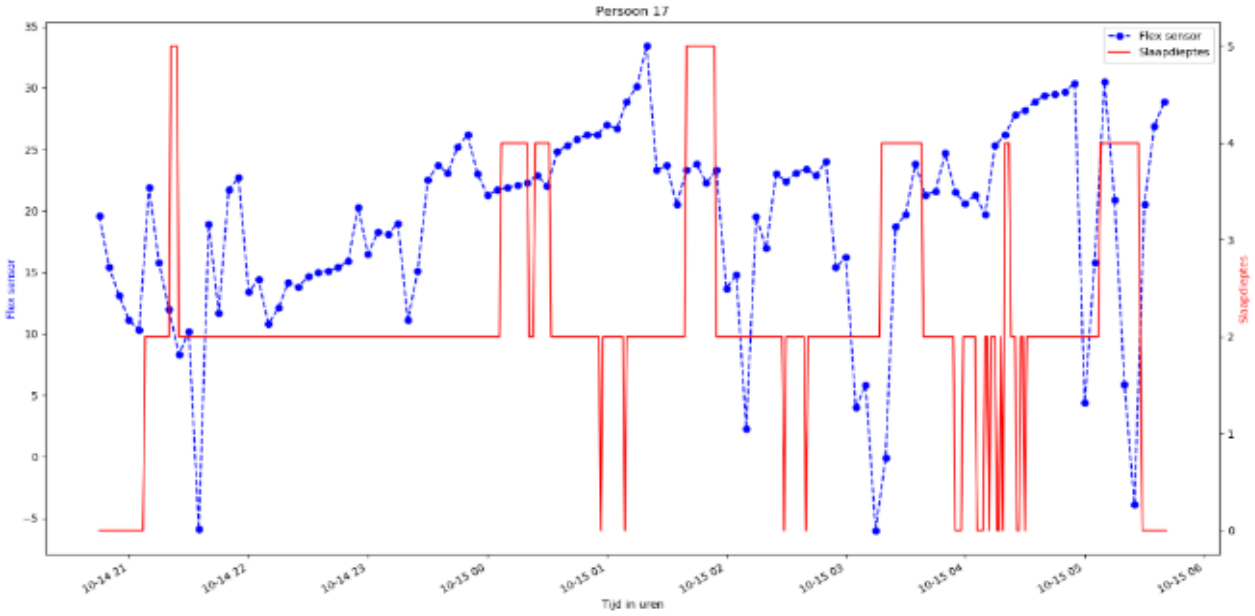


Figure 3-4:A plot of the results of the sleep phases measured by the Sensewear and the restless behavior measured by the Flexsensor for one subject for one night. High values of the flexsensor (blue) is restless behavior and low values of the Sensewear indicated awakenings.

3.6. Questionnaires

Table 3-3 shows the results that are obtained from the questionnaires for indoor air quality (HOPE) and the sleep quality (PSQI, GSQS and sleep diary). The IAQ of the HOPE questionnaire show a significant difference for location B (p = .035). Subjects considered a better indoor air quality with the high ventilation rate. The subjects of location A considered the air fresher with HVR (p = .026) but experienced more air draft in the bedroom (p = .041) (appendix C).

Table 3-3: The Hope, PSQI, GSQS and sleep diary for conditions high ventilation and low ventilation for both location A and location B (average, SD).

	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

GSQS (0-14)	4.6 ±2.5	4.2 ±2.5	.717	3.2 ±1.6	3.8 ±2.4	.396	.149	.690
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

3.7. Correlations

3.7.1. Bedroom parameters and building characteristics

For both locations, the CO_2 concentration has a significant negative correlation with the ACH (Figure 3-5) and a positive correlation with the number of persons in the bedroom for location A. Also, a correlation between the noise and the ACH was analyzed (Figure 3-5). Table 3-4 shows the correlations coefficient (*r*) and the *p*-values between the measured bedroom parameters and the building characteristics for location A (Table 3-4) and for location B (Table 3-5).

Table 3-4: Correlations (r-coefficient and p-value) between measured bedroom parameters, building types, and subject characteristics for **location A** (correlations are presented in bold).

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

Table 3-5: Correlations (r-coefficient and p-value) between measured bedroom parameters, building types, and subject characteristics for **location B** (correlations are presented in bold).

		Volume bedroom	ACH	Building year	Persons in bedroom
Temp	*r (p-value)*	-.33 (.160)	-.24 (.311)	.37 (.104)	.10 (.689)
RH	*r (p-value)*	-.21 (.385)	**-.74 (.001)**	**.49 (.027)**	.20 (.407)
CO_2	*r (p-value)*	**-.42 (.067)**	**-.81 (.001)**	.25 (.284)	**.65 (.002)**
Noise	*r (p-value)*	-.32 (.141)	.32 (.151)	-.24 (.292)	-.17 (.439)

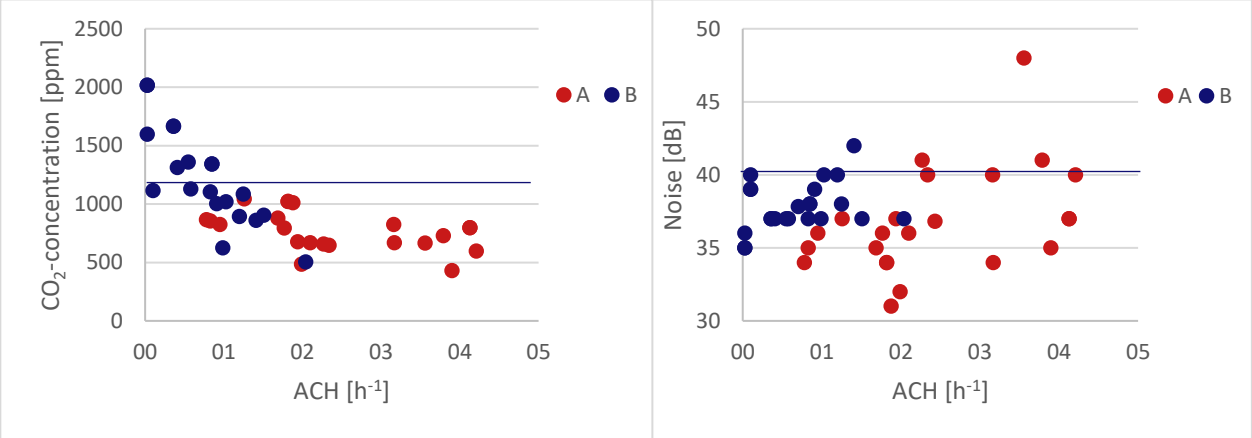


Figure 3-5: Plot of the CO_2 concentration [ppm] and air change per hour (ACH) (left) and the Noise and Air Change per Hour (ACH) (right) of location A and location B. The horizontal blue lines indicate 1200 ppm and 40 dB (Dutch Building Standard).

3.7.2. Indoor parameters and objective sleep quality results

The only correlation observed between the indoor parameters and the objective sleep quality results (measured with the Sensewear), is between the CO_2 concentration and the lying down of the subjects on location B (r = .51, p = .021). The correlations are included in Appendix C7 for location A and for location B.

3.7.3. Indoor parameters and subjective sleep quality results

The correlation between the indoor parameters (noise, temperature, RH and CO_2) and the subjective sleep quality results are shown in Table 3-6 for location A and in Table 3-7 for location B.

For both locations a correlation was observed between the temperature and the latency, and between the temperature and the efficiency. The CO_2 concentration correlates with the length of sleep, the awakenings, and the efficiency.

Table 3-6: Correlations (r-coefficient and p-value) between the indoor air parameters (noise, temperature, RH, CO_2) and the subjective sleep quality results for **Location A** (correlations are presented in bold).

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

Table 3-7: Correlations (r-coefficient and p-value) between the indoor air parameters (noise, temperature, RH, CO2) and the subjective sleep quality results for **Location B** (correlations are presented in bold).

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

3.7.4. 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 tests show a correlation for the length of sleep ($r > .3$, $p < .05$) for both locations (Table 3-8).

Table 3-8: Correlation between the sleep quality obtained by Sensewear (SW) and sleep diary questionnaire (Ques).

	Location A			Location B		
	SW	**Ques**	***r* (*p*-value)**	**SW**	**Ques**	***r* (*p*-value)**
Length of sleep [hr]	6.23 ±1.1	7.15 ±1.3	**.53(.063)**	6.82 ±0.95	7.6 ±1.5	**.47(.026)**
Latency [mn]	41.4 ±38.6	51.1 ±49.5	.06(.844)	17.9 ±20.7	30 ±41.1	**.53(.011)**
Awakenings [n]	6.12 ±3.1	0.39 ±0.64	.11(.726)	7 ±2.8	0.45 ±0.63	-.07(.753)
Sleep efficiency [%]	82 ±9.5	90 ±8.2	-.16(.605)	83 ±8.3	93 ±8.9	-.04(.865)

The IAQ was objectively measured with the logger (temperature, CO_2, RH), and subjectively with the HOPE questionnaire (temperature and IAQ). The results (Table 3-9) show a moderate correlation ($r > .3$) between the IAQ measured objectively or subjectively.

Table 3-9: Correlations (r-coefficient and p-value) between the objective and subjective measured indoor air quality parameters. (correlations are presented in bold).

Location A		**Noise**	**Temp**	**RH**	**CO_2**
HOPE	*r (p-value)*	**.31** (.180)	**.46** (.057)	**-.33** (.151)	**-.38** (.096)

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

3.8. Gender

The results of both the objective and subjective measured indoor air quality and sleep quality are divided into the results of men and women. All the results are presented in Appendix C4. Table 3-10 shows only the results with a significant difference. The length of sleep and awakenings did not show a difference between men and women, however the hope questionnaire showed that the temperature perception (men 9.7 vs women 13.5) and the perception of indoor air quality in the bedroom (men 11.1 vs women 16.1) were rated significantly more negative by women. Meanwhile the objective bed temperature was not significantly different between women and men.

Table 3-10: Differences in rating between men and women of the objective and subjective variables describing indoor air 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

3.9. Age

The participants are divided into age groups of over 55 years and younger than 55 years (Table 3-11). All the results and difference (*p*-value) are shown in Appendix C. The results of the sleep diary (subjective) show a significant difference. 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).

Table 3-11: 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**

4. Discussion

The aim of this study was to examine if there is a relation between the Indoor Air Quality and the sleep quality of ageing adults in two different conditions (low and high ventilation rate). The two conditions should therefore be significantly different in CO_2 levels. A MVHR system was used to influence the CO_2 levels and achieve a controlled ventilation rate, compared to recent studies were a window/door was opened closed (Mishra, van Ruitenbeek, Loomans, & Kort, 2018) (Liao & Laverge, 2019). These recent studies, and the study of Strom-Tejsen et.al. are conducted with students. However, the majority of our population are middle-aged men and women. Therefore, this study has included ageing adults leading an orderly life.

4.1. Subjects

In total 275 households were approached to participate in this study. However only 25 people responded and could be included based on the criteria. Two persons did not full fill the study, due to the high impact on their sleep and daily live, as motivated by the subjects. The inclusion of less than 10% was unexpectedly low, and a reason for this is not clear. Most probably people are reserved to have the measurements in the bedroom, but this has to be confirmed in a future study.

Both women and men were included in the present study. However, women and men judge different about indoor air quality, in particular thermal comfort. Women expressed worse dissatisfaction, they rated indoor air quality (Hope questionnaire, range 10-66) at 32 points, while men rated indoor air quality at 23 points, a significant difference. More dissatisfaction with women was also reported by the study of (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, sleep only 6.5 hours per night (Eekhof & Scherptong-Engbers, 2016). Also sleep characteristics appear to change at higher age, as 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 with a significant difference in the subjective measured depth of sleep (reduced) and awakenings (increase) for the participants older than 55 years.

4.2. Bedroom conditions

The outdoor conditions, as measured in the present study, reflect the time of the year, with low temperatures and a high RH. Although these conditions were significantly different at location A between the two weeks of the measurements, this did not affect the indoor conditions (r = -.088 p = .711).

The RH was significantly lower measuring 47% to 59% RH. Only at location A (with the high ventilation rate) a reduced RH was observed at a ventilation rate of as high as 91 m^3/h. The average values are well within the range for comfortable and healthy dwellings from NEN 15251 (NEN, 2007).

Bedroom temperature remained stable at both locations and was not significantly different between both locations. This is most likely the direct result of the MVHR system, in combination with the restriction to keep bedroom windows closed. This finding was also reported by Strøm-Tejsen et al, who supplied air directly with a ventilator (without heat recovery), and did not observe a difference in bedroom temperature (Strøm-Tejsen, Zukowska, Wargocki, & Wyon, 2016) (Strøm-Tejsen, Wargocki, Wyon, & Zukowska, 2014). In contrast, Mishra did observe a significant difference in temperature, but this was most likely the result of opening bedroom doors and windows to create a difference in ventilation rate (Mishra, van Ruitenbeek, Loomans, & Kort, 2018).

The CO_2 levels increased rapidly within the bedrooms to rather constant levels within two hours. The effect of a higher ventilation rate was significant at both location A and location B. However, CO_2 levels were higher at location B, most likely due to the lower ventilation rate. Although all CO_2 levels were high, they were only above acceptable levels (1200 ppm) at location B when the MVHR system was set at a low ventilation rate.

The difference in average CO_2 levels between both conditions (LVR and HVR) is for location A 182 ppm and for location B 402 ppm. This difference is much less when compared to the previous study of Strøm-Tejsen et al. (2016 and 2014), were the difference between both conditions (mechanical ventilation on/off) was 1925 ppm and 1560 ppm. Previous studies were performed with no ventilation or mechanical ventilation, compared with this study were the MVHR system was changed in ventilation rate, but mechanical ventilation was never switched of. This is most likely the reason for the different results with the studies from Strøm-Tejsen et al.

Bedroom noise was significantly higher (p = .003) at a high ventilation rate at both locations. However, the measured sound pressure level was not different between the two locations at a high ventilation rate (location A 39 dB; location B 39 dB), while the ventilation rate was about three times higher. This finding clearly shows the different characteristics of MVHR systems.

4.3. On body measurements

In this study, on body measurements were obtained with the use of actigraphy (Sensewear armband) to qualify sleep quality. From the data the length of sleep, latency, awakenings a sleep efficiency can be derived. The results were not significantly different for the two conditions for both locations.

Sleep quality from the participants appeared to be different between the two locations. The length of sleep was higher at location B (6.8 hrs) results when compared to location A (5.8 hrs) (p = .045), and the number of awakenings was also higher at location B (7.0) versus location A (5.1). This may be related to the higher average age (55 year vs 45 year) of participants at Location B.

In addition to the Sensewear a Flexsensor is used to obtain objective results for sleep quality by measuring restless behavior. However, of the 15 subjects that were provided with a Flexsensor, the data from only seven subjects was reliable. Because of this lack of data, no statistical analysis was performed. From figure

3-5 can be observed that the data did however correlate with the Sensewear, and therefore the Flexsensor can be used as an addition to the Sensewear when carried out successfully.

4.4. Questionnaires

Most studies on sleep quality used questionnaires to combine findings of subjects in a particular setting, or to differentiate between two settings (Strøm-Tejsen, Zukowska, Wargocki, & Wyon, 2016) (Mishra, van Ruitenbeek, Loomans, & Kort, 2018).

In the present study validated questionnaires were used to qualify the IAQ (Hope questionnaire) and the sleep quality (the Pittsbury Sleep Quality Index (PSQI), the Groningen Sleep Quality Scale (GSQS) and sleep diary). The results of sleep quality questionnaires did not show a significant difference between a low versus a high CO_2 level at either location. This was also observed in the studies of Chenxi, Strøm-Tejsen and Mishra. The only difference was observed in the rating of the indoor air quality. The higher ventilation rate (lower CO_2 level) was judged better overall. According to the subjects, there was more fresh air (also observed by Chenxi et.al. and Strøm-Tejsen et.al.), but the air draft was higher with the high ventilation rate.

For both locations the CO_2 concentration correlates with the length of sleep and the sleep efficiency, which both increase when the CO_2 levels increases. Although there is a correlation noted, length of sleep is highly dependent on the lifestyle of the subject.

Comparing the on body measurement and the questionnaires revealed that the length of sleep and the latency to sleep were showing the same tendency. 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 the sleep diary.

4.5. Limitations

The inclusion of less than 10% from a total of 275 households may result in a group of subjects not representative of the overall population. It might be useful in a future study to ask those people who did not want to participate their reasons to do so. Also, the reduction of the study load by limiting the number of study days may be helpful to increase the participation rate.

The average results of four nights are compared with the average results of the first two night for both the objective and the subjective results (Appendix C6). There is no significant difference between the results, and they show a strong correlation. Measuring two nights can be considered in further research.

At the start of the study, the main question was to investigate the effect of a nightly increase in bedroom CO_2 on sleep quality of ageing adults. Because of the low inclusion of ageing adults at location A, a second location (B) had to be included.

All participants had to adjust the ventilation rate themselves, at the time they went to sleep. So, they were aware of sleeping with a low or high ventilation rate. This may affect the answers to the questionnaires. A few participants found an increase in background noise at a high ventilation rate unpleasant, which might have affected their perception of sleep quality. The CO_2 levels in the room of subject 10 are very low and showed little difference between the two conditions. This is most likely due to not following the study directions.

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. Limitation of the number of questionnaires may be helpful to reduce this problem.

This study has investigated only sleep at night, and not intentional and unintentional napping during daytime. In particular elderly have shown to be sleepier during the day, than younger adults (Carskadon, Van den Hoed, & Dement, 1980), most likely because they do not have enough sleep at night (Craskadon & Dement, 2011). Therefore, napping during daytime should be included in the measurements in future research.

4.6. 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 test 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 appeared to increase at a high ventilation rate by ca. 3 decibels. The questionnaire should include a question to have a subjective judgement of noise, for comparison.

Analysis of the results showed that although there were differences between the objective and subjective measured sleep quality indicators, a moderate correlation between the results exists. Therefore, it can be suggested to use only one questionnaire, to measure the sleep quality, in addition to the Sensewear. This is in line with the suggestion of Mishra et.al. (Mishra, van Ruitenbeek, Loomans, & Kort, 2018).

4.7. Practical implementation

The use of a mechanical ventilation system with heat recovery (MVHR) was essential in the present study, because it allows to control the bedroom environment. However, MVHR systems appeared to function differently between buildings. The ventilation rate appeared to be significantly higher at location A (low 42 m^3/h; high 91 m^3/h) if compared to location B (low 15 m^3/h; high 31 m^3/h). This resulted in a high variation in ventilation rates and most likely in difference in IAQ. Location A meets the requirements of the regulations of The Dutch Building Standard, instead of Location B, were in both conditions the average ventilation rate is lower than the requirements for newly build homes. The measured sound pressure level at a high ventilation rate (39 dB ±3.7) should be considered when selecting a MVHR system, as it reduces sleep quality, and may stimulate people to lower the ventilation rate.

In general, a higher ventilation rate and therefore higher ACH was accompanied by a lower bedroom CO_2 concentration (Figure 3.5). More importantly, at an ACH above 2.0 h^{-1}, the CO_2 concentration remained below 900 ppm, which is the acceptable level as recommended by the European advisory board (NEN, 2007). At an ACH above 1.5 h^{-1}, the CO_2 concentration remained below 1200 ppm, which is acceptable according to the Dutch Building Standard.

Analyses of the number of persons in a bedroom revealed that the CO_2 concentration was higher when two people shared one bedroom (LVR 1471 ppm, HVR 1020 ppm), if compared to only one person in a bedroom (LVR 944 ppm, HVR 744 ppm). Prevention of the high CO_2 levels may be achieved with a CO_2-controlled ventilation system. These systems are presently applied in many new buildings, and have the advantage to reduce energy consumption significantly (Chenari, Lamas, Gaspar, & Manuel Carlos, 2017).

During the intake it was observed that several filters of MVHR systems were not replaced on time. Also, most of the subjects normally use only level 1 of the system and four of the subjects of Location B3 turned off the air supply permanently, because of the air draft and the noise. There was a lack of knowledge and information about the system among the participants. To make the system work properly the users of the apartments must be informed properly about the system.

5. Conclusion

The aim of the present study was to examine if there is a relation between the indoor air quality, indicated by CO_2 levels, and the sleep quality of ageing adults. The change in CO_2 levels has been realized with a MVHR system, which results in differences between the ventilation rates among the subjects. These different ventilation rates were correlated with the bedroom CO_2 levels. However, no correlation was analyzed between the CO_2 levels and the sleep quality. The subjects did report the bedroom air to be significantly fresher with a lower CO_2 level (high ventilation rate). Characteristics of the subjects appeared to have a significant effect on sleep conditions (age) and on indoor air quality perception (gender).

6. Acknowledgement

This report describes my master thesis for the master Building Physics and Services at the Eindhoven University of Technology. The project was a new experience for me, and I am proud to present this final report. This thesis was not possible with the help of many people, therefore I want to thank several people for their cooperation in this project. Firstly, Helianthe Kort and Marcel Loomans (TU/e), Paul Vink and Niek Smook (VIAC), my supervisors, for their guidance during the project. Eigen Haard and SSW for their enthusiasm to work with me and to bring me in contact with potential participants. All the subjects who volunteered in the study, without their participation this study would not have succeeded. Furthermore, I would like to thank Wout van Bommel for his explanations and help with the measurement equipment in the BPS laboratory. At last, I would like to thank my family and friends for their great support during my study period.

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8. Appendices

Appendix A Method

- **A1 Characteristics of the participants**
- **A2 Ventilation rate in the bedroom**
- **A3 Overview of used measurement equipment**

Appendix B Questionnaires

- **B1 Sleep diary and GSQS**
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- **C1 CO2 concentration for one night of all subjects**
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Appendix A Method

A1 Characteristics of the participants
A2 Ventilation rate in the bedroom
A3 Overview of used measurement equipment

A1 Characteristics of the participants

Table 8-1: Characteristics of the participants: number, gender, age, location and study date.

Number start	Number in research	Gender	Age	Location/building	Study date		Specialties
					Week 1 LVR	Week 2 HVR	
1	1	Female	64	A	18-3-2019	1-4-2019	
2	2	Male	33	A	18-3-2019	25-3-2019	2 persons in bedroom
3	-						Resigned
4	3	Male	49	A	18-3-2019	25-3-2019	
5	4	Female	54	A	18-3-2019	25-3-2019	
6	5	Female	28	A	18-3-2019	25-3-2019	2 persons in bedroom
7	6	Male	27	A	18-3-2019	25-3-2019	2 persons in bedroom
8	7	Male	33	A	18-3-2019	25-3-2019	
9	8	Female	67	A	18-3-2019	25-3-2019	
10	9	Female	41	A	8-4-2019	22-4-2019	
11	10	Female	56	A	8-4-2019	15-4-2019	
12	11	Male	59	A	8-4-2019	15-4-2019	
13	-						Resigned
14	-						Power outlet
15	12	Female	56	B2	14-10-2019	4-11-2019	
16	13	Female	29	B2	14-10-2019	21-10-2019	2 persons in bedroom
17	14	Male	30	B2	14-10-2019	21-10-2019	2 persons in bedroom
18	15	Female	59	B1	25-11-2019	18-11-2019	2 persons in bedroom
19	16	Male	27	B3	11-11-2019	19-11-2019	
20	17	Male	78	B3	12-11-2019	18-11-2019	
21	18	Female	72	B3	12-11-2019	18-11-2019	
22	19	Female	81	B3	18-11-2019	25-11-2019	2 persons in bedroom

23	20	Male	82	B3	18-11-2019	25-11-2019	2 persons in bedroom
24	21	Female	34	B3	18-11-2019	2-12-2019	
25	22	Male	28	B4	2-12-2019	9-12-2019	
26	-						Resigned

A2 Ventilation rate in the bedroom

Table 8-2: Measured ventilation rate [m^3/h] and calculated air change per hour (ACH) (ventilation rate/volume of the room) per subject.

Number start	Bedroom area	Location /building	Measured ventilation rate		Air Change per Hour (ACH)	
	[m^2]		LVR [m3/h]	HVR [m3/h]	LVR	HVR
1	6.4	A	30	65	1.94	4.21
2	14.9	A	45	113	1.94	4.21
3	14.9	A	45	113	1.26	3.16
4	14.4	A	61	123	1.77	3.56
5	12.1	A	24	68	0.83	2.34
6	11.2	A	49	111	1.82	4.13
7	11.2	A	49	111	1.82	4.13
8	12.1	A	49	92	1.69	3.17
9	10.7	A	20	54	0.78	2.10
10	11.0	A	25	60	0.95	2.27
11	10.5	A	50	98	1.99	3.90
12	12.2	A	55	111	1.88	3.79
13	-	A				
14	12.1	B1	17	32	0.58	1.1
15	11.1	B2	1	3	0.03	0.1
16	11.0	B2	1	3	0.03	0.1
17	11.0	B2	1	3	0.03	0.1
18	12.1	B1	12	30	0.41	1.03
19	13.3	B3	22	45	0.58	1.2
20	9.1	B3	20	31	0.91	1.41
21	12.9	B3	26	39	0.83	1.25
22	12.7	B3	11	26	0.36	0.85
23	12.7	B3	22	26	0.36	0.85
24	17.6	B3	42	86	0.99	2.04

25	14	B4	20	55	0.55	1.51
26	9.5	B4	13	21	0.52	0.84

Table 8-3: Ventilation rate [m^3/h] for each bedroom, compared to the regulations in the Dutch Building Code.

Number start	Bedroom area	VR DBC	VR DBC	Location /building	Measured VR		Meets requirements
	[m^2]	[l/s]	[m^3/h]		LVR	HVR	
1	6.4	5.76	20.74	A	30	65	Yes
2	14.9	13.41	48.28	A	45	113	Yes
3	14.9	13.41	48.28	A	45	113	Yes
4	14.4	12.96	46.66	A	61	123	Yes
5	12.1	10.89	39.20	A	24	68	Yes
6	11.2	10.08	36.29	A	49	111	Yes
7	11.2	10.08	36.29	A	49	111	Yes
8	12.1	10.89	39.20	A	49	92	Yes
9	10.7	9.63	34.67	A	20	54	Yes
10	11.0	9.9	35.64	A	25	60	Yes
11	10.5	9.45	34.02	A	50	98	Yes
12	12.2	10.98	39.53	A	55	111	Yes
13	-			A			
14	12.1	10.89	39.20	B1	17	32	No
15	11.1	9.99	35.96	B2	1	3	No
16	11.0	9.99	35.64	B2	1	3	No
17	11.0	9.99	35.64	B2	1	3	No
18	12.1	10.89	39.20	B1	12	30	No
19	13.3	11.97	43.09	B3	22	45	Yes
20	9.1	8.19	29.48	B3	20	31	Yes
21	12.9	11.61	41.76	B3	26	39	No
22	12.7	11.43	41.15	B3	11	26	No
23	12.7	11.43	41.15	B3	22	26	No
24	17.6	15.84	57.02	B3	42	86	Yes

25	14	12.6	45.36	B4	20	55	Yes
26	9.5	8.55	30.78	B4	13	21	No

A3 Overview of used measurement equipment

Table 8-4: Used equipment for objective measurements of indoor air quality and sleep quality for each subject.

Number in research	Logger	Transmitter IAQ	Transmitter flex	Sensewear
1	ID3598 EL 12078	18725	5247	31 (pro2)
2	ID3602 EL 12220	18744	6001	7 (pro2)
3	ID3602 EL 12220	18745	4438	34 (pro2)
4	ID3598 EL 12078	18713	6899	33 (pro2)
5	ID3598 EL 12078	18714	6936 A	4 (pro2)
6	ID3598 EL 12078	18714	6936 B	24 (pro2)
7	ID3598 EL 12078	18716	5249	35 (pro2)
8	ID3598 EL 12078	18732	2580	1 (pro2)
9	ID3598 EL 12078	18725	5127	No number (pro2)
10	ID3598 EL 12078	19158	2577	12 (pro2)
11	ID3602 EL 12220	19155	4438	3 (pro2)
12	ID3702 EL 12325	18726	2403	9
13	ID 3601 EL 12219	19158	4286	2
14	ID 3601 EL 12219	19158	6778	8
15	ID3703 EL 12325	18726	6778	10
16	ID 3598 EL 12078	18716		7
17	ID3602 EL 12220	18713	4438	4
18	EL 12336	18744		13
19	ID3602 EL 12220	18737	4438	11
20	ID3602 EL 12220	18737		No number
21	EL 12337	19156		6
22	ID3703 EL 12325	18726	6778	8

Appendix B Questionnaires

B1 Sleep diary and GSQS
B2 PSQI
B3 HOPE

B1 Sleep diary and GSQS

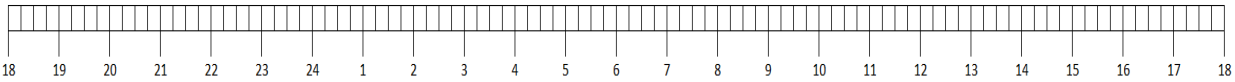
OCHTEND VRAGENLIJST

Datum _____

Tijdstip in bed _____

Tijdstip uit bed

	Slapen	x	In bed zonder slapen	Tijdstip waarop het licht uitgaat



1 Hoe beoordeelt u uw slaapkwaliteit van de afgelopen nacht?

	1	2	3	4	5	
zeer slecht						zeer goed

2 Heeft u lichamelijke klachten deze ochtend? (zo ja, omschrijf deze klachten)

_____

3 Geef een cijfer aan de slaapkwaliteit van vannacht door een nummer tussen 1 tot 7 te kiezen.
Mijn slaap vannacht was...

	1	2	3	4	5	6	7	
erg diep								erg licht
erg kort								erg lang
onderbroken								onafgebroken
dromeloos								veel dromen
erg rusteloos								erg rustgevend

4 Waar werd u wakker van vanochtend?

- ☐ Een gezette alarmklok
- ☐ Geluid
- ☐ Ongemak
- ☐ Spontaan
- ☐ Anders: _____

De volgende vragen kunnen alleen met Ja **of** Nee beantwoord worden.

5 Ik heb diep geslapen vannacht

- ☐ Ja
- ☐ Nee

6 Ik heb het gevoel dat ik slecht heb geslapen vannacht

- ☐ Ja
- ☐ Nee

7 Het duurde meer dan een half uur voordat ik in slaap viel

- ☐ Ja
- ☐ Nee

8 Ik ben meerdere keren wakker geworden vannacht

- ☐ Ja
- ☐ Nee

9 Ik voelde me moe nadat ik wakker werd vannacht

- ☐ Ja
- ☐ Nee

10 Ik heb het gevoel dat ik niet genoeg slaap heb gekregen vannacht

- ☐ Ja
- ☐ Nee

11 Ik ben midden in de nacht opgestaan

- ☐ Ja
- ☐ Nee

13 Ik heb het gevoel dat ik maar een paar uur heb geslapen vannacht

- ☐ Ja
- ☐ Nee

14 Ik voel dat ik goed heb geslapen vannacht

- ☐ Ja
- ☐ Nee

15 Ik heb geen oog dicht gedaan vannacht

- ☐ Ja
- ☐ Nee

16 Ik had geen problemen om in slaap te vallen afgelopen nacht

- ☐ Ja
- ☐ Nee

17 Nadat ik 's nachts wakker werd had ik moeite om in slaap te vallen

- ☐ Ja
- ☐ Nee

18 Ik heb de hele nacht liggen draaien in bed

- ☐ Ja
- ☐ Nee

19 Ik heb minder dan 5 uur geslapen vannacht

- ☐ Ja
- ☐ Nee

B2 PSQI

Pittsburgh Sleep Quality Index (PSQI)

INVULLEN VOOR DE START VAN HET ONDERZOEK

Datum _____

De volgende vragen hebben betrekking tot uw slaapgewoonten gedurende de **afgelopen maand**. De antwoorden moeten een goede afspiegeling zijn van de dagen en nachten in de afgelopen **maand**.

Graag alle vragen beantwoorden.

Gedurende de afgelopen maand,

1 Hoe laat bent u gewoonlijk naar bed gegaan? _____

2 Hoe lang (in minuten) duurt het voordat u in slaap valt? _____

3 Hoe laat bent u gewoonlijk opgestaan uit bed? _____

4 Hoeveel uur slaapt u per nacht gemiddeld (kan afwijken van de tijd die u in bed doorbrengt)? _____

		Niet in de afgelopen maand	Minder dan 1 keer per week	Een of twee keer per week	Drie of meer keer per week
5	Gedurende de afgelopen maand, hoe vaak had u problemen met slapen doordat u…				
a	niet kon slapen binnen 30 minuten				
b	wakker werd midden in de nacht of vroeg in de ochtend				
c	op moest staan om naar het toilet te gaan				
d	niet comfortabel kon ademen				
e	moest hoesten of last had van hard snurken				
f	het te koud had				
g	het te warm had				
h	nachtmerries/ nare dromen had				
i	pijn voelde				
j	andere redenen, graag ook omschrijven hoe vaak				

		Niet in de afgelopen maand	Minder dan 1 keer per week	Een of twee keer per week	Drie of meer keer per week
6	Gedurende de afgelopen maand, hoe vaak heeft u medicijnen gebruikt om in slaap te komen?				

		Niet in de afgelopen maand	Minder dan 1 keer per week	Een of twee keer per week	Drie of meer keer per week
7	Gedurende de afgelopen maand, hoe vaak heeft u moeite om wakker te blijven tijdens het autorijden, het eten van een maaltijd of bij sociale activiteiten?				

		Geen moeite	Een klein beetje moeite	Enigszins moeite	Erg veel moeite
8	Gedurende de afgelopen maand, hoe moeilijk was het om enthousiast te blijven over dingen die u gedaan moest krijgen?				

		Erg goed	Redelijk goed	Redelijk slecht	Erg slecht
9	Gedurende de afgelopen maand, hoe beoordeelt u de kwaliteit van u slaap?				

		Geen partner of kamergenoot	Partner of kamergenoot in de andere kamer	Partner in dezelfde kamer maar niet in hetelfde bed	Partner in hetzelfde bed
10	Heeft u een bedpartner of kamergenoot?				

		Niet in de afgelopen maand	Minder dan 1 keer per week	Een of twee keer per week	Drie of meer keer per week
	Als u een bed of kamergenoot heeft, vraag hem/haar hoe vaak u in de afgelopen maand last had van:				
a	Hard snurken				
b	Lange adempauzes tijdens het slapen				
c	Trekken of schokken van de benen tijdens het slapen				
d	Periode van desorientatie of verwaaring tijdens de slaap				
e	andere onrust terwijl u slaapt, graag omschrijven ook hoe vaak				

B3 HOPE

HOPE Vragenlijst

1 Heeft u afgelopen nacht last gehad van de volgende symptomen (meerdere antwoorden mogelijk)?

- ☐ droge/jeukende ogen
- ☐ verstopte neus
- ☐ hoesten of kuchen
- ☐ droge keel
- ☐ vermoeidheid of sufheid
- ☐ duizeligheid
- ☐ pijn of stijfheid in de nek en/of schouders
- ☐ hoofdpijn

2 Heeft u het idee dat deze klachten worden veroorzaakt door de slaapomgeving?

- ☐ Ja
- ☐ Nee

3 Als deze klachten al voorkwamen, heeft u het idee dat deze worden versterkt door de slaapomgeving?

- ☐ Ja
- ☐ Nee

4 Hoe heeft u vannacht de **temperatuur** in uw slaapomgeving ervaren?

	1	2	3	4	5	6	7	
comfortabel								oncomfortabel
stabiel								varieert sterk
geen beweging								tocht
heet								koud

5 Wat was de temperatuur idealiter vannacht?

- ☐ warmer
- ☐ geen verandering
- ☐ kouder

6 Hoe heeft u vannacht de **luchtkwaliteit** in uw slaapomgeving ervaren?

	1	2	3	4	5	6	7	
tevreden								ontevreden
droog								vochtig
fris								bedompt
geurloos								vies ruiken

7 Wat voor kleding had u vannacht aan (bij benadering)?

- ☐ geen kleding
- ☐ ondergoed
- ☐ lichte slaapkleding (met korte mouwen)
- ☐ warme slaapkleding (met lange mouwen)

Appendix C Results

C1 CO_2 concentration for one night
C2 Normality test
C3 HOPE questionnaire
C4 Results man and woman and significant difference
C5 Results per age
C6 Four nights compared to two nights
C7 Correlations

C1 CO_2 concentration for one night

While subjects were in bed, the CO_2 concentration remained rather constant, although a gradual increase during the first hour was observed in several bedrooms at a low ventilation rate (Figure 8-1).

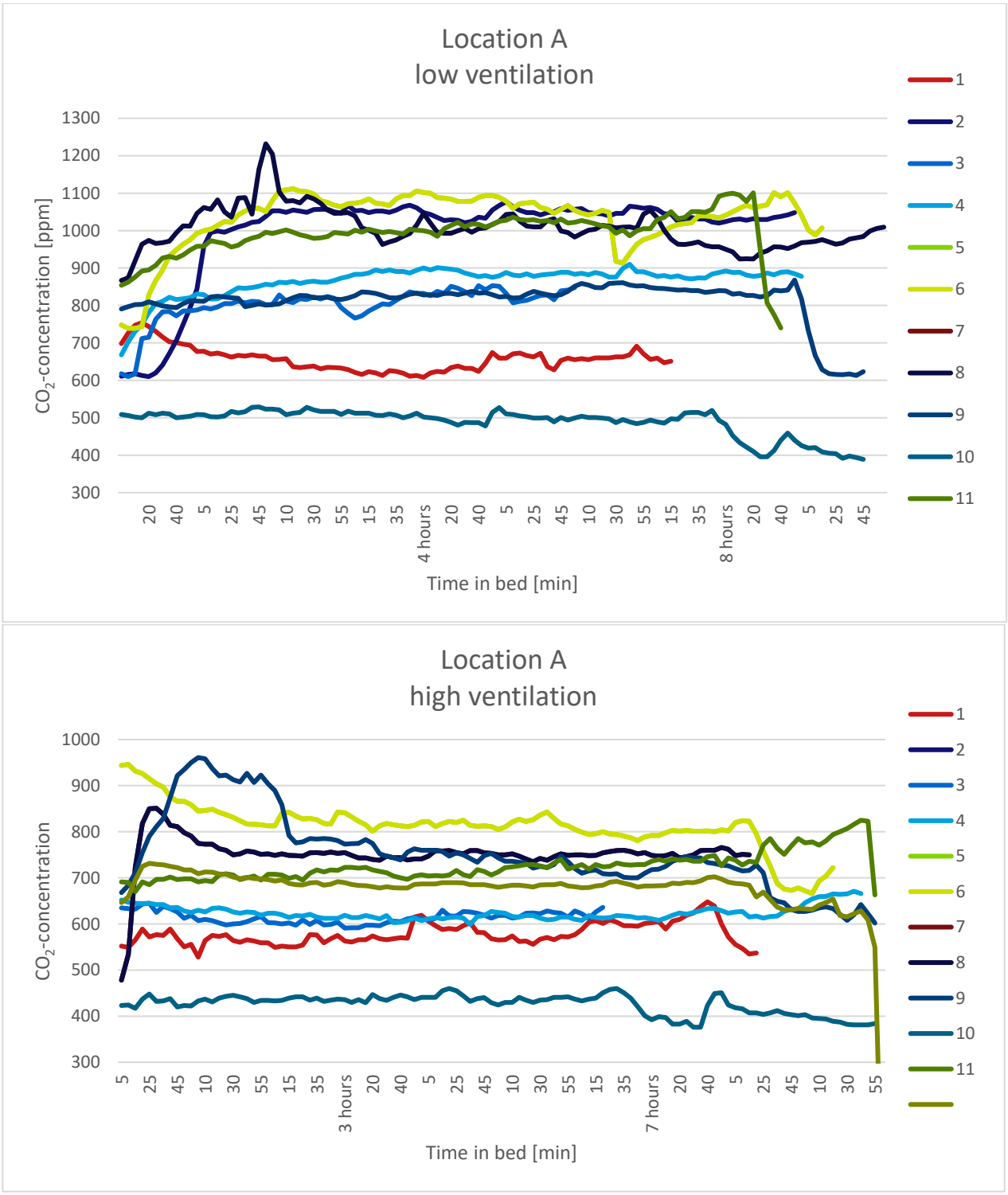


Figure 8-1: CO_2 concentration [ppm] measured during the second night of the four night episode, presented for all 11 subjects of location A. Top: low ventilation rate. Bottom: high ventilation rate.

While subjects were in bed, the CO_2 gradually increased in several bedrooms, at a low ventilation rate (Figure 8-2). Sudden decreases in CO_2 levels have been due to opening doors, this can be confirmed by data from the sleep diary.

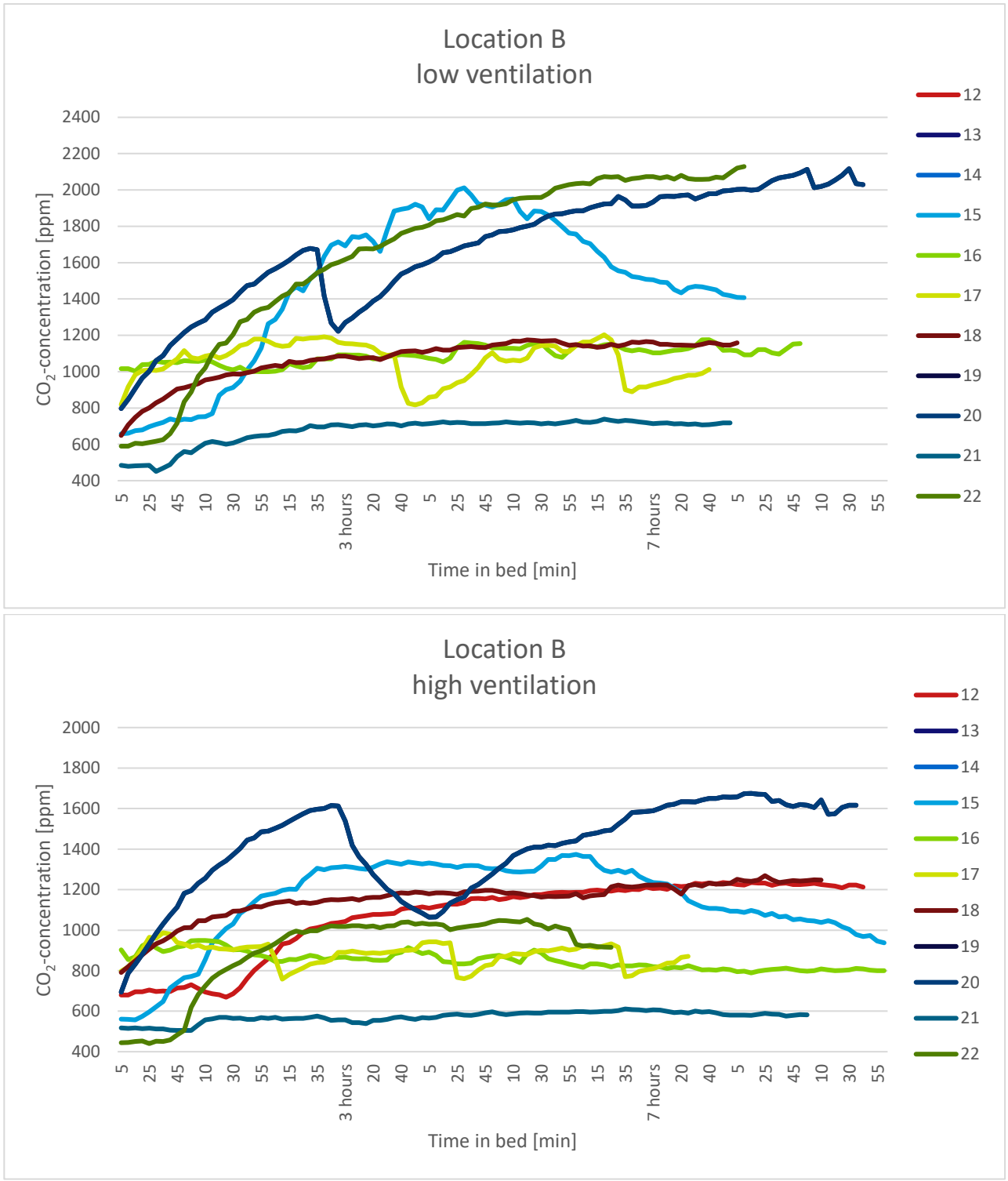


Figure 8-2: CO2 concentration [ppm] measured during the second night of the four night episode, presented for all 11 subjects of location B. Top: low ventilation rate. Bottom: high ventilation rate.

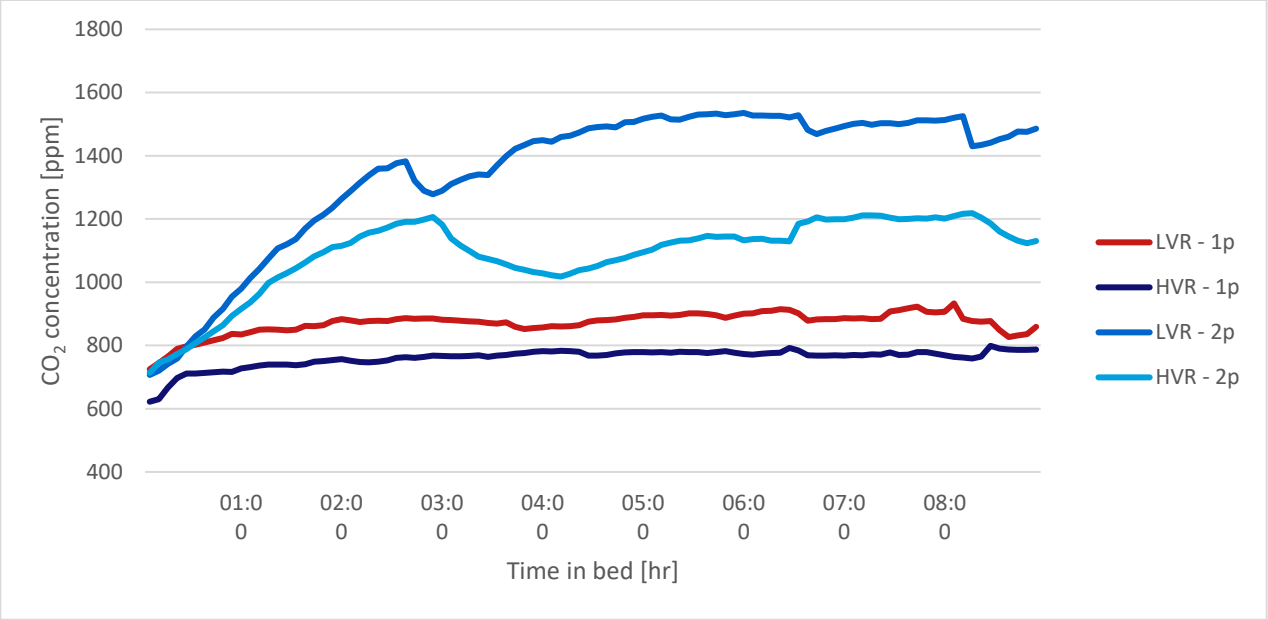


Figure 8-3: Average CO_2 concentration [ppm] measured during the second night for the bedroom with 1 person (1p) and with two persons (2p) for both conditions.

C2 Normality test

Table 8-5: Results of normality test.

	Location A			Location B		
	LVR	**HVR**	**Difference P-value**	**LVR**	**HVR**	**Difference P-value**
Outdoor						
Temperature	**< 0.001**	**< 0.001**	**0.022***	**0.004**	**0.045**	0.531*
RH	**< 0.001**	**< 0.001**	**0.003***	0.192	0.107	0.733
Bedroom						
Temperature	0.486	0.228	0.348	**0.031**	**< 0.001**	0.313*
RH	0.606	0.057	**0.016**	0.083	0.956	0.148
CO_2	0.134	0.183	**< 0.001**	0.772	0.526	**< 0.001**
Noise	0.399	0.169	**0.003**	**0.011**	0.361	**0.007***
Ventilationrate	0.109	0.084	**< 0.001**	0.251	0.234	**< 0.001**
ACH	**0.016**	0.093	**0.003***	0.259	0.311	**< 0.001**

* test for significant difference is performed with the Wilcoxon Ranks test.

C3 HOPE questionnaire

Table 8-6: Detailed results of the Hope questionnaires.

	Location A			Location B		
	LVR	**HVR**	**Difference *p*-value**	**LVR**	**HVR**	**Difference *p*-value**
Physical complains	1.0 ±1.2	1.2 ±1.7	.726	1.1 ±1.5	1.2 ±1.6	.441
Temperature Total score	11.8 ±4.2	12.6 ±3.6	.465	10.7 ±4.3	11.8 ±3.9	.206
Comfortable	2.7 ±1.7	2.9 ±1.7	.754	2.6 ±1.0	2.8 ±1.0	.484
Stable	2.2 ±1.3	2.5 ±1.1	.828	2.4 ±1.1	2.4 ±0.9	.745
Air draft	2.2 ±1.0	3.4 ±1.9	**.041**	2.1 ±1.2	2.7 ±1.6	.140
To hot/cold	3.8 ±1.9	3.7 ±2.5	.600	3.2 ±1.2	3.3 ±1.4	.493
Indoor Air Quality Total score	15.2 ±4.2	14.2 ±3.9	.307	13.8 ±4.3	11.8 ±3.5	**.035**
Satisfaction	3.1 ±1.9	2.8 ±1.6	.535	3.1 ±1.4	2.7 ±1.4	.120
Dry air	4.5 ±2.1	4.5 ±1.6	1.00	4.8 ±1.4	4.7 ±1.34	.741
Fresh air	3.6 ±1.8	2.5±1.4	**.026**	3.7 ±1.6	3.3 ±1.6	.314
Smell of the air	2.7 ±1.4	2.2 ±1.3	.086	3.3 ±1.6	2.9 ±1.6	.104

C4 Results men and women and significant difference

Table 8-7: Total results of the indoor air quality and sleep quality, both objective and subjective measured, for man and woman. When the *p*-value is < .05, there is a significant difference. These values are presented in bold.

	Man	Women	Difference *p*-value
Bedroom			
Temperature [°C]	19.4 ±0.8	18.9 ±0.8	.092
RH [%]	53 ±7.5	51 ±8.2	.824
CO_2 [ppm]	1032 ±340	953 ±403	.543
Noise [dB]	37.7 ±3.5	37 ±2.2	.293
Sensewear			
Lying down [hr]	7.5 ±1.3	8.1 ±1.0	.301
Length of sleep [hr]	6.3 ±1.1	6.6 ±0.9	.213
Latency [mn]	37.8 ±33.9	40.9 ±52.4	.851
Awakenings [n]	6.8 ±3.4	6.0 ±2.2	.325
Efficiency [%]	83 ±7.6	83 ±9.4	.864
Sleep			
Stage 0 [%] *Awake*	19.1 ±7.6	20.2 ±15.2	.892
Stage 1 [%] *light sleep*	54.6 ±9.2	51.37 ±10.4	.634
Stage 2 [%] *deep sleep*	20 ±8.3	20.4 ±7.6	.356
Stage 3 [%] *very deep sleep*	7.2 ±2.7	7.9 ±3.5	.352
Hope	22.65 ±7.7	32.2 ±5.6	**.003**
Temperature	9.7 ±4.1	13.5 ±3.1	**.032**
IAQ	11.1 ±3.01	16.1 ±3.6	**< .001**
PSQI	5.2 ±1.8	4.8 ±2.5	.474
GSQS	4.0 ±2.3	4.0 ±2.3	.860
Quality of sleep	3.2 ±0.7	3.1 ±0.6	.548
Depth of sleep	17.1 ±6.1	18.7 ±3.3	.375
Sleep diary			

Length of sleep [hr]	6.9 ±1.3	7.7 ±1.1	.057
Latency [mn]	38.1 ±34.1	43.4 ±40.0	.503
Awakenings [n]	0.3 ±0.5	0.6 ±0.8	.054
Sleep efficiency [%]	91 ±7.0	91 ±8.8	.787

C5 Results per age

Table 8-8: Results of the objective and subjective measurements of the indoor air quality and the sleep quality, divided in two age groups: < 55 years and > 55 years. The significant difference (p = > .05) is presented in bold.

	< 55 year	> 55 year	Difference *p*-value
Bedroom			
Temperature [°C]	19.2 ±0.9	19.0 ±0.7	.743
RH [%]	53 ±9.3	51 ±6.1	.443
CO_2 [ppm]	973 ±397	1003 ±359	.739
Noise [dB]	37.4 ±3.0	37.3 ±2.7	.893
Sensewear			
Lying down [hr]	7.6 ±1.2	7.9 ±1.1	.159
Length of sleep [hr]	6.3 ±1.0	6.6 ±1.0	.493
Latency [mn]	49 ±45	29 ±40	.320
Awakenings [n]	7.3 ±3.1	5.5 ±2.4	.939
Efficiency [%]	82 ±7.2	84 ±9.7	.537
Sleep			
Stage 0 [%] *Awake*	20.3 ±8.5	18.3 ±14.9	.533
Stage 1 [%] *light sleep*	54.3 ±8.8	22.8 ±9.8	.360
Stage 2 [%] *deep sleep*	17.8 ±5	22.8 ±9.8	.535
Stage 3 [%] *very deep sleep*	7.8 ±2.1	7.3 ±3.9	.648
Hope	28.2 ±6.7	27.1 ±9.5	.480
Temperature	12.2 ±3.4	11.2 ±4.6	.282
IAQ	13.9 ±3.1	13.5 ±5.0	.599
PSQI	4.6 ±2.0	5.3 ±2.4	.269
GSQS	3.7 ±2.0	4.2 ±2.6	.477
Quality of sleep	3.3 ±0.6	3.0 ±0.7	.232
Depth of sleep	20.0 ±2.9	15.6 ±5.6	**.019**
Sleep diary			

Length of sleep [hr]	7.2 ±1.3	7.5 ±1.3	.523
Latency [mn]	38 ±31	44 ±43	.404
Awakenings [n]	0.3 ±0.5	0.6 ±0.8	**.003**
Sleep efficiency [%]	91 ±6.6	90 ±9.2	.435

C6 Four nights compared to two nights

Table 8-9: Significant difference (*p*-value) and correlations (*r*-coefficient and *p*-value) between measured indoor air quality and sleep quality for two nights compared to four nights.

	LVR			HVR		
	4 night	**2 nights**	**Difference Correlation**	**4 night**	**2 nights**	**Difference Correlation**
Bedroom						
CO_2 [ppm]	1142 ±421	1146 ±426	.692 .992 (>.001)	825 ±251	832 ±290	.570 .992 (>.001)
Sensewear						
Lying down [hr]	7.7 ±1.0	7.8 ±1.0	.356 .898 (>.001)	7.8 ±1.3	7.6 ±1.3	.131 .935 (>.001)
Length of sleep [hr]	6.5 ±0.9	6.5 ±0.9	.603 .904 (>.001)	6.3 ±1.2	6.3 ±1.3	.494 .951 (>.001)
Latency [mn]	34 ±38	36 ±43	.319 .989 (>.001)	43 ±46	40 ±42	.405 .948 (>.001)
Awakenings [n]	6.5 ±2.6	6.7 ±3.5	.517 .901 (>.001)	6.4 ±3.2	6.2 ±3.0	.421 .961 (>.001)
Efficiency [%]	84 ±7.4	84 ±8.6	.831 .952 (>.001)	82 ±9.7	82 ±10.0	.552 .951 (>.001)
Hope	27.8 ±8.5	27.8 ±9.5	.941 .973 (>.001)	27.5 ±8.3	27.5 ±8.3	.932 .953 (>.001)
GSQS	4.6 ±2.6	5.0 ±2.4	.386 .859 (>.001)	4.2 ±2.6	4.3 ±3.4	.805 .939 (>.001)
Quality of sleep	3.1 ±0.5	3.2 ±0.7	.342 .699 (>.001)	3.2 ±0.8	3.4 ±1.7	.464 .347 (.113)
Depth of sleep	17.3 ±4.9	17.4 ±4.9	.820 .916 (>.001)	18.5 ±5.1	18.4 ±5.7	.757 .936 (>.001)
Sleep diary						
Length of sleep [hr]	7.3 ±1.4	7.3 ±1.3	.736 .928 (>.001)	7.3 ±1.3	7.2 ±1.2	.101 .944 (>.001)
Latency [mn]	45.4 ±41.9	45.4 ±40.6	.989 .992 (>.001)	36.3 ±33.5	41.1 ±34.8	.048 .955 (>.001)
Awakenings [n]	0.5 ±0.7	0.7 ±1.0	.298 .873 (>.001)	0.4 ±0.6	0.4 ±0.7	.762 .932 (>.001)
Sleep efficiency [%]	90 ±9.2	90 ±8.2	.328 -.461 (.031)	92 ±6.7	91 ±7.8	.077 .972 (>.001)

C7 Correlations

Table 8-10: Correlations (r-coefficient and p-value) between measured bedroom parameters, building types ,subject characteristics for **location A** (r > 0.4 assume a moderate correlation, p < .05 indicate a significant correlation, both presented in bold).

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

Table 8-11: Correlations (r-coefficient and p-value) between measured bedroom parameters, building types ,subject characteristics for **location B** (r > 0.4 assume a moderate correlation, p < .05 indicate a significant correlation, both presented in bold).

		Volume bedroom	ACH	Building year	Persons in bedroom
Temp	*r (p-value)*	-.33 (.160)	-.24 (.311)	.37 (.104)	.10 (.689)
RH	*r (p-value)*	-.21 (.385)	**-.74 (.001)**	**.49 (.027)**	.20 (.407)
CO_2	*r (p-value)*	**-.42 (.067)**	**-.81 (.001)**	.25 (.284)	**.65 (.002)**
Noise	*r (p-value)*	-.32 (.141)	.32 (.151)	-.24 (.292)	-.17 (.439)

Table 8-12: Correlations (r-coefficient and p-value) between measured bedroom parameters and objective sleep quality results for location A. r > 0.4 assume a moderate correlation, p < .05 indicate a significant correlation, both presented in bold.

		Noise	Temp	RH	CO_2
Lying down	*r (p-value)*	-.21 (.501)	-.18 (.568)	.04 (.893)	.13 (.663)
Length of sleep	*r (p-value)*	-.27 (.371)	-.16 (.625)	.10 (.752)	.20 (.503)
Latency	*r (p-value)*	-.03 (.928)	.07 (.838)	-.04 (.903)	-.01 (.969)
Awakenings	*r (p-value)*	-.19 (.527)	.13 (.680)	.26 (.383)	-.02 (.956)
Efficiency	*r (p-value)*	.05 (.861)	.01 (.995)	03 (.933)	.01 (.976)

Table 8-13: Correlations (r-coefficient and p-value) between measured bedroom parameters and objective sleep quality results for location B. r > 0.4 assume a moderate correlation, p < .05 indicate a significant correlation, both presented in bold.

		Noise	Temp	RH	CO_2
Lying down	*r (p-value)*	-.17 (.440)	-.17 (.482)	.24 (.310)	**.51 (.021)**

Length of sleep	*r (p-value)*	-.39 (.072)	-.08 (.747)	.22 (.360)	.36 (.115)
Latency	*r (p-value)*	.23 (.298)	-.25 (.295)	23 (.323)	-.04 (.862)
Awakenings	*r (p-value)*	-.09 (.696)	.11 (.646)	.26 (.279)	.24 (.317)
Efficiency	*r (p-value)*	-.39 (.076)	.07 (.781)	.05 (.849)	-.06 (.811)

Table 8-14: Correlations (r-coefficient and p-value) between the indoor air parameters (noise, temperature, RH, CO_2) and the subjective sleep quality results for **Location A**. r > 0.3 assume a moderate correlation, p < .05 indicate a significant correlation, both presented in bold.

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

Table 8-15: Correlations (r-coefficient and p-value) between the indoor air parameters (noise, temperature, RH, CO2) and the subjective sleep quality results for **Location B**. r > .3 assume a moderate correlation, p < .05 indicate a significant correlation, both presented in bold.

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